Master Thesis

Analysis of a central S-train network extension in the Greater Copenhagen Area

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Technical University of Denmark
DTU Management Engineering
MSc.Eng. Transport and Logistics
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Preface

This report is the final product of a 30 ECTS credits Master Thesis and carried out on the study line Transport and Logistics at the Department of Management Engineering, Technical University of Denmark (DTU).

The project began August 1st, 2019, with hand-in at January 17th, 2020, and has to be finished with an oral defence January 28th, 2020.

The report is divided into several chapters, where the first chapter consists of the introduction to the report. The second chapter introduces the current state of the S-train network and the remaining public transport network in the Greater Copenhagen Area. The third chapter evaluates the need for a new S-train tunnel and this analysis is written on the basis of an evaluation of the capacity consumption, delays and population development.

Chapter 4, 5 and 6 describe the theory and methodology behind timetabling of S-trains in RailSys and public transport models. Chapter 7 introduces the socio-economic analysis which is conducted for the two scenarios in the project.

The report is ended with a discussion which discusses the theory, methodology and the results. It also describes other possible ways to analyse more scenarios for the development of the S-train network. Finally, the report is terminated with a conclusion on the empirical findings and results and concludes how the project can be further extended.

A list of abbreviations and quantities for formulas is presented in the beginning of the report. In the end, a reference list and a list of figures presents an overview of the relevant literature and an overview of the presented figures in the report.

Frederik Wrona Holgersen

Kongens Lyngby, January 17th, 2020
Abstract
This report investigates an implementation and an analysis of an extension of the S-train network in the Greater Copenhagen Area. The extension is implemented as a tunnel in the central parts of Copenhagen from the stations Emdrup and Hellerup in the northern parts of Copenhagen to the stations Valby and Ny Ellebjerg in the southern parts and is throughout the report named the Express Tunnel. The name refers to its main purposes which are to implement an alternative tunnel in Copenhagen for the S-trains and to reduce the travel time in the public transport.

The report is introduced with a description of the different public transport modes and their design and main functions. Since the report investigates S-trains, this transport mode is explained in more details. The report also introduces upcoming projects as extensions to the existing network and the primary resource for this introduction and selection is the plan “Trafikplan 2032” by the Danish Transport, Construction and Housing Agency. Projects, which are not mentioned in the report about Trafikplan 2032 are not included in this project’s analysis.

Calculations of the capacity consumption on lines in the S-train network illustrate that the capacity consumption in the central part of the network will be reduced in the future as a benefit from the new signalling system CBTC. Therefore, it will be possible to run more trains through Copenhagen in the future which is also a demand from an increased population in the municipalities in the suburbs. However, approximately 38% of all delays and cancellations in the network are caused by an incident in the central part and a major part of the delays are not caused by signalling and interlocking failures only. On the basis of these statistics, it is considered that a new tunnel and is able to reduce the travel time and an alternative to the Boulevard Tunnel.

The Express Tunnel is analysed in two scenarios where the common stations are Forum and Vibenshus Runddel. The difference between Scenario 1 and Scenario 2 is an additional station at Rigshospitalet which extends the travel time through the new tunnel.

With a view to reduce the travel time significantly between the radial lines in the S-train network, the existing fast lines in the network, Bx, E and H, are operated via the new tunnel and the stopping train lines, A, B, and C via the Boulevard Tunnel. Line Bx is changed to K and operates every 10 minutes and a new line, line L, is introduced as a supplement via the Boulevard Tunnel. Since the skip-stop-service on the radial lines is kept, it is not possible to raise the maximum number of trains through the central parts of Copenhagen from 30 per hour today to 42.

The extended S-train network leads to significant travel time reductions between the radial lines up to 14 minutes depending on direction and origin and destination.
Furthermore, the travel time to and from Nørreport Station as well as the metro lines are also reduced from the radial lines.

With the new tunnel and new timetable, including an increased level of service on the radial lines, an increase in the number of passengers is expected from the radial lines by more than 25% on some lines. On the other hand, the number of passengers on Ringbanen and the Boulevard Tunnel is decreased significantly with reductions by more than 25%.

On the basis of the socio-economic analysis it is concluded that whether Scenario 1 nor Scenario 2 is socio-economically profitable with an internal rate of return by 0.9% and 1.4% respectively. However, profitability for Scenario 2 is still higher than for Scenario 1 despite the higher construction costs. It is therefore suggested that a higher utilisation of the infrastructure in both tunnels in Copenhagen should be carried out to improve the travel time savings and the profitability.

Finally, the report recommends that more analyses of the Express Tunnel and of the S-train network in general should be conducted before decision of the construction. It is recommended that an analysis of a metro-style operation vs. the current operation has to be carried out and evaluated as well as an additional analysis of the new tunnel in OTM. Likewise, a simulation in RailSys is also preferred to investigate how a higher utilisation of the infrastructure including new lines and existing stations affects the punctuality.
Acknowledgement

First and foremost, I would like to show my gratitude to my supervisors at DTU, Stefan Eriksen Mabit and Henrik Sylvan for their enthusiasm and guidance with my project. It has been a great inspiration and motivation for me to be guided throughout the process and to present my findings and results during the thesis period.

I would also like to show my gratitude to Bernd Schittenhelm and Anders Lank Bislev, Banedanmark, for guiding me through RailSys and to let me use a license key for the software. I am very grateful for having the opportunity to use a basic model for the S-train network with basic infrastructure and timetable. It has been very motivated for me to explain my results and to discuss my findings and methods with them.

Afterwards, I will like to express my appreciation to Michael Pihl Jørgensen and Rie Jensen and other colleagues in COWI for their great help with finding unit prices, standards and the right contacts on other employees that could help with my project about expertise for signalling systems and tunnels.

I will also show my gratefulness to the staff behind the National Transport Model at Transport DTU for providing me a licence and a pc for using the model. I am grateful for being admitted to the material for the previous course in the National Transport Model.

A special thanks to Tobias Molich, Banedanmark, for guiding me with the National Transport Model and for advising me about the structure in public transport networks in GIS. Moreover, I will also like to thank Joachim Bak and Daniel Aundal, DSB, for providing me data about delays in the S-train network.

Finally, I will show my deepest gratitude to Steen Koefoed and Tina Norre from Ekspresgruppen for inviting me to meetings with stakeholders such as the Ministry of Transport, DSB, Dansk Industri and several municipalities in the capital region. It has also been a motivation factor in my project to present and discuss my thesis and my findings with them.

Last, but not least, I would like to thank my family, friends and especially my fiancée Rikke for always being patient with me and for their support throughout the master thesis period. It has also been very helpful and a motivation for me with the interest that all of them have showed in my project and my results.
# Abbreviations

The following tables give an overview of used abbreviations and physical quantities in the report.

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Term</th>
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<tbody>
<tr>
<td>AADT</td>
<td>Annual Average Daily Traffic</td>
</tr>
<tr>
<td>AAWT</td>
<td>Annual Average Weekday Traffic</td>
</tr>
<tr>
<td>CBA</td>
<td>Cost-benefit-analysis</td>
</tr>
<tr>
<td>CBTC</td>
<td>Communication Based Train Control</td>
</tr>
<tr>
<td>GIS</td>
<td>Geographical Information System</td>
</tr>
<tr>
<td>HKT</td>
<td>HastighedsKontrol og Togstop</td>
</tr>
<tr>
<td>UIC</td>
<td>Union Internationale de Chemin de fer – The International Union of Railways.</td>
</tr>
<tr>
<td>SA/SE</td>
<td>Class name for DSB S-train units (8 cars/4 cars)</td>
</tr>
<tr>
<td>LTM</td>
<td>National Transport Model (Danish: Landstrafikmodellen)</td>
</tr>
<tr>
<td>TERESA</td>
<td>Transportministeriets Regnearksmodel for Samfundsøkonomisk Analyse for transportområdet</td>
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<table>
<thead>
<tr>
<th>Station abbreviation</th>
<th>Station name</th>
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<tbody>
<tr>
<td>Ba</td>
<td>Ballerup</td>
</tr>
<tr>
<td>Bud</td>
<td>Buddinge</td>
</tr>
<tr>
<td>Dbt</td>
<td>Dybbølsbro</td>
</tr>
<tr>
<td>Fm</td>
<td>Farum</td>
</tr>
<tr>
<td>Fs</td>
<td>Frederikssund</td>
</tr>
<tr>
<td>Gl</td>
<td>Glostrup</td>
</tr>
<tr>
<td>Hi</td>
<td>Hillerød</td>
</tr>
<tr>
<td>Hi</td>
<td>Hellerup</td>
</tr>
<tr>
<td>Hot</td>
<td>Holte</td>
</tr>
<tr>
<td>Htå</td>
<td>Høje Taastrup</td>
</tr>
<tr>
<td>Kh</td>
<td>København H (Copenhagen Central Station)</td>
</tr>
<tr>
<td>Kj</td>
<td>Køge</td>
</tr>
<tr>
<td>Kk</td>
<td>Østerport</td>
</tr>
<tr>
<td>Kl</td>
<td>Klampenborg</td>
</tr>
<tr>
<td>Kn</td>
<td>Nørreport</td>
</tr>
<tr>
<td>Sam</td>
<td>Svanemøllen</td>
</tr>
<tr>
<td>Sjæ</td>
<td>Sjælør</td>
</tr>
<tr>
<td>Næl</td>
<td>Ny Ellebjerg</td>
</tr>
<tr>
<td>Und</td>
<td>Hundige</td>
</tr>
</tbody>
</table>
### Definition:
A station in parentheses indicates that a line is exclusive this station. Example: (Svanemøllen)-Hellerup-Hillerød indicates that a specific statement concerns the line from Svanemøllen to Hellerup and Hillerød (including both stations) and not Svanemøllen itself.
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1 Introduction

Today, the public transport network in the capital region in Denmark consists of several different public transport operators and transport modes. The S-train network and the network of regional trains and long-distance trains are operated by DSB, the metro network is operated by Metroselskabet, the network of bus lines is planned by Movia and operated by different operators and, finally, the local train network in Northern Zealand and from Køge towards Faxe Ladeplads and Rødvig is operated by Lokaltog. This report illustrates and explains all the different parts of the current public transport network in the entire region. However, the main focus is on the S-train network, since the topic of this project covers an extension of the S-train network.

The report introduces the S-train network including the current lines and upcoming projects as well as the rolling stock. The rolling stock, the DSB class SA/SE, is the primary rolling stock and running times and timetables in this project will be calculated based on this type of rolling stock since the properties of future rolling stock are uncertain.

Furthermore, the report makes the case that some radial lines in the S-train network have an untapped capacity potential. The only exceptions are the lines Dybbølsbro-Hundige and Hellerup-Holte at which the skip-stop-service almost utilises the capacity completely. In the future, it might be possible to operate more trains through the congested central part from Dybbølsbro to Svanemøllen since the new signalling system CBTC reduces the theoretical headway. However, since the report demonstrates that an impact in the central part causes many delays in the entire network, it might be beneficial to investigate an alternative to the current central part. The report proposes an alternative tunnel to potentially improve the travel times and the reliability in the network.

On the basis of a new so-called Express Tunnel, the report investigates the benefits in the entire network. The S-train network is completely changed compared to the current timetable S20 as the basis, since the fast lines on the radial lines will be operated through the Express Tunnel and the stopping lines via the existing tunnel. The final product will be a timetable for all lines in the new network which is changed with two different scenarios for the Express Tunnel as well as an upgrade of the depot track at Âmarken Station for reversing trains. Moreover, the capacity consumption on all lines is also presented after the change.

The new timetable and the profitability in constructing the new tunnel will also be analysed and evaluated. The assignment model in the National Transport Model (LTM) will be carried out and be based on the timetable for the two timetable scenarios. The final product from this investigation will then be to analyse the passenger flows in the public transport network in the Greater Copenhagen Area and to evaluate on the changes.
Finally, the results from LTM are applied in the excel sheet TERESA for carrying-out a socio-economic analysis of the profitability. Furthermore, the strategical benefits and disadvantages will also be further commented.

Chapter 2 introduces the network of public transport in the capital region. The primary focus is the S-train network and this transport mode is introduced in more details. However, the other transport modes on railways - the metro, regional trains, local trains and light rail – are also introduced and elaborated, whereas buses only are mentioned briefly. Chapter 3 evaluates the need for a new alternative tunnel for the S-trains as well as an introduction for the two alternative alignments for the Express Tunnel. The explanation for the need is based on capacity consumption, travel times and data about incidents on the central part of the network.

In chapter 4, the theory and methodology behind running time calculations and timetabling is introduced in a detailed way. Furthermore, this chapter also introduces the timetabling- and simulation program RailSys, and this introduction mentions the functions and tools which have been applied to create new timetables for the S-trains. Moreover, the signalling system CBTC is also explained. The timetabling procedure and method are covered in chapter 5. This procedure is based on a list with conditions for the process. It also explains the changes of the basic model in RailSys, since the Express Tunnel is digitalised into it.

Chapter 6 introduces the National Transport Model and the public assignment model. It also explains how the two scenarios for the Express Tunnel are modelled in LTM and how the existing network of public transport will be connected to it. The main results from LTM are applied to the socio-economic analysis, which is introduced and explained in chapter 7. The empirical findings and main results from the project are discussed in chapter 8 which also puts the results into perspective to other future projects. Finally, chapter 9 covers the conclusion for the report.

In the end, the report introduces appendices concerning an overview of the scenarios in the project. The appendices illustrate schematic drawings of the S-train infrastructure, public timetable for the S-train lines in the scenarios, differential maps from the route choice calculations and finally passenger loads in the network in the scenarios.

### 1.1 Problem statement and learning objectives

The following problem statement applies to the master thesis and its objective:
• It will be investigated if the implementation of an Express Tunnel will result in a passenger increase and a reduction in travel time for the existing passengers in the public transport network in the Greater Copenhagen Area, and if the tunnel is profitable in a socio-economic analysis.

In order to answer the problem statement, the following project objectives are formulated:

1) Describe the design of the current public transport network and present upcoming infrastructure extensions in Copenhagen and in the capital region

2) Analyse the current train service and capacity consumption in the S-train network and evaluate the need for an extension of the infrastructure

3) Formulate scenarios for the S-train network with the new Express Tunnel

4) Apply RailSys to model the Express Tunnel and to determine running times with the scenarios and classify advantages and disadvantages with these

5) Explain the structure in a transport model and apply the Express Tunnel and the scenarios and results from RailSys to it

6) Analyse and evaluate the results from a transport model and apply them to a socio-economic analysis

7) Evaluate the profitability of the project together with sensitivity analyses and formulate a conclusion on the project as a basis for decision making

2 The network of public transport

This chapter introduces the current network of public transport in the Greater Copenhagen Area. Afterwards, the future planned upgrades and extensions of the public transport network are introduced and determined if these should be included the analyses.

In this chapter the public transport network is divided up into S-trains, metro, railway lines (regional trains and local train lines) and buses. The main focus throughout the report will be on the S-trains since the topic involves this transport mode. However, the other transport modes are mentioned and defined since these are included in the analysis.


2.1 Method

Since the chapter has to introduce and investigate the current and upcoming network of public transport in the Greater Copenhagen Area it is necessary to determine the number of stops and lines on a basis year. For this purpose, the year 2020 has been selected as the basis year and the current network of public transport as well as the lines and stops, timetables and headways are based on this year. It means that upcoming extensions of the network as well as new timetables are not included directly in this introduction, but these will be elaborated afterwards in the evaluation for new public transport lines.

Since the public transport network in the assignment model is based on the National Transport Model, the existing and future public transport network in the entire country are included. However, this project investigates only the Greater Copenhagen Area and adjacent networks to it in the capital region and it has therefore been decided to include the public transport network from this area in the description.

The project is primarily based on the S-train network and it means that this public transport mode will be elaborated in a more detailed way than other transport modes. It is chosen to do so, since the running time calculations and further analyses in this project are based on an extension of the S-train network and not for other transport modes.

It is determined to base the rolling stock for the S-train network on the current S-train fleet of 4th generation S-trains. In the future after the completion of this project, the S-train network might undergo a transition from the current S-train network to a new driverless public transport system with a need for new rolling stock (DSB, 2019). During this project, however, the technical specifications of new rolling stock are not published which means that it is not possible to determine other requirements and properties for rolling stock than already specified. Therefore, it is assumed in this project that the existing rolling stock in the S-train network will cover the new extended network.

Furthermore, this project will not cover the current and future rolling stock for other transport modes, since no analyses and calculations will be conducted on other types of rolling stock than the S-train units. Instead, the running times and headways for these transport modes will only be based on the timetables for the route choice calculations.

In the year 2019 the new metro line, Cityringen, as well as the new high-speed line between Copenhagen and Ringsted with the new station Køge Nord have been opened to the public. The maps, which show the geographical network of the transport modes, are generated in the GIS-software ArcMap. For this purpose, data with the alignments for the transport network were already digitalised in GIS from the course Public Transport Planning in 2015. However, this digital transport network is slightly modified, since Enghave Station was replaced by Carlsberg Station in 2016, some stations on Cityringen got other names than specified at that time, and the new line from Copenhagen to Ringsted via Køge Nord Station was opened to the public in 2019. Furthermore, the
alignment for the upcoming light rail line in Ring 3 is also changed to a new alignment within the campus area in DTU Lyngby Campus and the upcoming metro line, Sydhavnsmetroen, is also digitalised into this public transport network. The new line from Copenhagen to Ringsted as well as Sydhavnsmetroen are drawn in GIS upon base maps showing the alignments. For simplicity, one specific transport mode at a time is presented throughout the chapter with a specific map showing the specified network. These maps are only illustrations for the public transport network and the analyses based in the assignment model are not based on this data but on specific data in LTM.

The technical specifications of the current fleet of S-train units are based on the course Railway Operations and Management from 2018. In this course, technical specifications of different kinds of Danish rolling stock were a part of the curriculum. However, these specifications are not used directly in simple timetable- and running time calculations, but they are applied to the timetable software RailSys, in which the timetable scenarios for this project have been conducted.

When it comes to the introduction of new planned extensions of the public transport network, different reports and presentations about new lines and new stations and stops have been investigated. The primary resource for considering new planned extensions of the railway and light rail network is the report “Trafikplan for den statslige jernbane 2017-2032” by the Danish Transport, Construction and Housing Agency from 2017. In this report, the planned extensions and timetables for the government-owned railway network in Denmark are listed as traffic plans for the basis years 2022, 2027 and 2032. Projects in the capital region, which are mentioned in this report and included in the National Transport Model (LTM), are assumed to be adopted and implemented. Other projects, which also are listed as considerations in this report, are at the current moment only proposals which means that they are not completely adopted. This is the case for e.g. the new stations in the S-train network Priorparken and Trylleskov and in order to determine if such projects with new stations should be included in the analysis, this decision is based on the report “Optimering af stationsstrukturen” by the Danish Transport, Construction and Housing Authority from 2014. In this report, future stations on different railway lines in the capital region as well as in other parts of Denmark are listed and determined, if the authority would recommend the stations or not. However, the new stations Vinge and Favrhholm are either already under construction or adopted by law, and such stations are applied to the timetable for the S-trains in this project. Another case is the construction of new metro lines, railway lines or light rail lines. If the construction act for these projects is adopted, these projects will also be included in the analysis. If the projects still undergo a discussion regarding alignment and stops, they are not included in the analysis since the uncertainty about their alignment and stations is too
high and, therefore, the model results could have a risk of not being accurate compared to the situation today.

2.2 S-trains

The main transport mode for this project is the S-train network which consists of the following lines (Larsen & Poulsen, 2009):

- Klampenborg-Vanløse-Frederiksberg was opened in 1934. Vanløse-Frederiksberg was replaced by the metro in 2000-2003, and the line from Flintholm was extended to Ny Ellebjerg in 2006. Today, the line Hellerup-Ny Ellebjerg is called Ringbanen.
- Valby-Copenhagen Central-Station-Hellerup was opened in 1934. Extended to Holte in 1936 and to Hillerød 1968.
- Valby-Vanløse was opened in 1941. This line was extended to Ballerup in 1949 and further to Frederikssund in 1989. Double-track to Frederikssund was finished in 2002.
- Svanemøllen-Farum from 1977.

Figure 1 illustrates the S-train network in the timetable S20 where the lines A, B, C and E have 10 min headway, while line F has a 5 min headway and line H a 20 min headway. Line Bx is a rush hour line with a 20 min headway. Dashed lines represent an extension of the lines with a train every 20 minutes.
The current network is, as mentioned, consisting of seven lines. In daytime on weekdays, the lines have a headway of a train every 10 minutes unless another headway is specified. The seven lines are:

- A: Hillerød-Hundige, extended to Solrød Strand every 20 min during peak hours
- B: Farum-Høje Taastrup
- Bx: Farum-Høje Taastrup. Only every 20 minutes and only during peak hours
- C: Klampenborg-Ballerup. Extended to Frederikssund every 20 minutes
- E: Holte-Køge
- F: Hellerup-Ny Ellebjerg. Every 5 minutes
- H: Østerport-Frederikssund. Only every 20 minutes

In weekends and Friday and Saturday nights, only the lines A, B, C and F are in operation and the network of lines is slightly changed.

The current network with all existing stations is illustrated in Figure 2 below.

In evening hours as well as on weekdays and holidays, the timetable and network are changed and the number of lines is reduced, i.e. the lines Bx, E and H are not in operation.

Figure 2: Current S-train network map based on daytime operation on weekdays from 2020-timetable (S20). All current stations are illustrated (DSB, 2019). Please note, that Vinge Station will be opened later in 2020.
in weekends and in evening hours. Since this project investigates the normal operation in
daytime on weekdays, the other timetables and line maps are not investigated in detail.
A geographical overview map of the S-train network is illustrated in Figure 3.

Figure 3: Overview map of the S-train network. The location of the upcoming new stations Vinge and Favrholm are also illustrated.

As observed in Figure 3, the network covers a major area of the capital region with long regional lines to other cities than Copenhagen and is more concentrated in the city area. It is also observed on the S-train map that all lines except line F from the suburbs outside the central parts of Copenhagen are operated through the city centre via Østerport, Nørreport and Copenhagen Central Station. Line F, which is called Ringbanen, runs from Hellerup to Ny Ellebjerg along the oldest line past Nørrebro. Thus, the design of the network with many radial lines with the same origin, the central part Svanemøllen-
Dybbølsbro, is the main characterisation of the S-train network in the capital region. Primarily, this design is a consequence from the former urban plan, Fingerplanen, *(the Finger Plan)* – illustrated in Figure 4, which was established in 1947 as the first urban plan in Denmark. This plan sketched the future development of the Greater Copenhagen Area and its surroundings as a hand with the central parts of Copenhagen as the palm and the new urban areas from the central parts and radial lines towards Køge, Roskilde, Frederikssund, Farum and Hillerød as fingers. The main public transport towards the new radials should be the S-trains and the old S-train lines were extended further into the radials when new towns and suburbs started to grow (Larsen & Poulsen, 2009). With this design, it should be possible to live in all suburbs around Copenhagen and have a direct line towards the city centre.

### 2.2.1 Rolling stock

The trainsets in the S-train network are operated by DSB. There are two types of trainsets: DSB Class SA and DSB Class SE with identical specifications, except the SA trainset consists of 8 cars and the SE consists of 4 cars. Both trainsets are normally named 4th generation S-trainsets and the previous generations are not in operation anymore. The SA and SE can also be coupled together for operating with longer trains. Up to two SA units can be coupled and up to four SE can be coupled to one train, whereas it is also possible to couple one SA with one SE (Landex, Rail Traffic Engineering - Spring 2014, 2014). The specifications are given as follows in Table 1 (Landex, Rail Traffic Engineering - Spring 2014, 2014).

<table>
<thead>
<tr>
<th></th>
<th>DSB class SA/SE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Length:</strong></td>
<td>83.72 m</td>
</tr>
<tr>
<td></td>
<td>42.58 m</td>
</tr>
<tr>
<td><strong>No. Seats:</strong></td>
<td>312</td>
</tr>
<tr>
<td></td>
<td>134</td>
</tr>
<tr>
<td><strong>Max. speed:</strong></td>
<td>120 km/h</td>
</tr>
<tr>
<td><strong>Start acceleration</strong></td>
<td>$a_0$: 1.2 m/s&lt;sup&gt;2&lt;/sup&gt;</td>
</tr>
<tr>
<td><strong>No. Trainsets:</strong></td>
<td>104</td>
</tr>
<tr>
<td></td>
<td>31</td>
</tr>
<tr>
<td><strong>Year:</strong></td>
<td>1997-2005</td>
</tr>
<tr>
<td><strong>Theoretical max. speed $v_{\text{max}}$:</strong></td>
<td>38.89 m/s</td>
</tr>
<tr>
<td><strong>Braking percentage C:</strong></td>
<td>175</td>
</tr>
<tr>
<td><strong>Braking ratio $c$:</strong></td>
<td>0.7</td>
</tr>
<tr>
<td><strong>Brake reaction time $t_{\text{br}}$:</strong></td>
<td>≈ 0 s</td>
</tr>
</tbody>
</table>

Table 1: Overview of S-trainset specifications. The number of trainsets in the fleet as well the number of seats are from (Nilsson, 2019).
For modern trainsets as the S-trains, the brake reaction time is very short and can be assumed to be equal to zero (Landex, Rail Traffic Engineering - Spring 2014, 2014). In this project, this will also be the case.

In the future, the existing fleet of S-trains might be replaced by a new generation of S-trains with another set of specifications. However, no information about new rolling stock for the S-train network is given at the present moment. Consequently, the running times for the S-trains are in this project based on the existing fleet of S-trains and, furthermore, the upcoming rolling stock may have similar technical specifications as the current trainsets.

### 2.2.2 Infrastructure

The infrastructure on the different lines in the S-train network are managed by Banedanmark and separated into different TIB-lines with a specified number (TIB stands for “Trafikal Information om Banestrækningen”). These lines are:

- 810: Copenhagen Central Station-Høje Taastrup
- 820: Copenhagen Central Station-Hillerød
- 830: Valby-Frederikssund
- 840: Svanemøllen-Farum
- 850: Copenhagen Central Station-Køge
- 860: Hellerup-Klampenborg
- 880: Ny Ellebjerg-Vigerslev-Hellerup

The maximum speed limit on the lines is 120 km/h. However, lower speed limits may apply to some lines:

- **810:**
  - Copenhagen Central Station-Valby: 90 km/h
  - Valby-Høje Taastrup: 120 km/h
- **820:**
  - Copenhagen Central Station-Østerport: 80 km/h
  - Østerport-Svanemøllen-Hellerup: 90 km/h
  - Hellerup-Lyngby: 120 km/h
  - Lyngby-Holte: 90 km/h
  - Holte-Hillerød: 120 km/h
- **830:**
  - Valby-Vanløse: 90 km/h
  - Vanløse-Frederikssund: 120 km/h
- **840:**
  - Svanemøllen-Buddinge: 90 km/h
  - Buddinge-Farum: 100 km/h
• 850:
  o Copenhagen Central Station-Skelbæk-Åmarken: 90 km/h – 100 km/h
  o Åmarken-Køge: 120 km/h
• 860: 100 km/h
• 880: 90 km/h
All S-train lines are double-tracked except only one part between Fiskebæk and Farum on the Farum radial line. Furthermore, the lines are electrified with 1,650 V DC contrary to the electrified lines for regional and intercity trains which are equipped with 25 kV 50 Hz AC. The system 1,650 V DC is therefore only implemented on the S-train network, whereas other DC systems in Denmark are for the metro and the light rail in Aarhus but with a lower voltage.

Schematic drawings of the S-train infrastructure for all lines are illustrated in Appendix 1. One special case about the infrastructure is Hellerup Station. Due to its complexity, this station is drawn on a specific layout plan and it is illustrated in Figure 5.

Figure 5: Schematic layout plan of Hellerup Station. The connection to the regional tracks, tracks 1 and 2, is not shown.

Finally, the S-train network is currently equipped with two different signalling systems. The existing system HKT (abbreviation for HastighedsKontrol og Togstop) is in operation in the entire network except the lines (Svanemøllen)-Hellerup-Hillerød as well as Ryparken-Klampenborg which are equipped with the new system CBTC. The network is, however, in the upcoming years undergoing a change from HKT to CBTC in the entire network. This is further commented on in chapter 3.

2.3 Metro
The Copenhagen Metro is an additional public transport system to the S-train. Currently, this system consists of three lines, and the fourth line, M4, will open in the beginning of 2020. The network is situated in three municipalities, Copenhagen, Frederiksberg and
Tårnby, and contrary to the S-train network the metro network covers Amager with two different lines. The infrastructure and rolling stock in the metro network are owned and managed by Metroselskabet, which is in coordination with its owners, the Ministry of Transport and Housing as well as the municipalities of Copenhagen and Frederiksberg (Ingvardson, 2019).

The first part of the network from Nørreport Station towards Vestamager and Lergravsparken was finished and opened to the public in 2002. In 2003, the network was extended to Frederiksberg and Vanlose upon the former S-train infrastructure, and in 2007 the line to Lergravsparken was extended to Copenhagen Airport (Den Store Danske, 2017). The new line M3 called Cityringen was opened to the public September 29th, 2019. The network is illustrated geographically in Figure 6.

Since the two different parts, the lines M1 as well as M2 and the new circular line Cityringen and the new line towards Nordhavn, are separated, they are illustrated as two networks. M1 and M2 are coloured in green while M3 and the upcoming M4-branch towards Orientkaj are coloured in red.

As the S-trainsets, the metro trainsets run on track with the gauge 1,435 mm. However, the metro trains are driverless, and the network is completely isolated from the S-train.
network. It means that this network should be seen as a parallel system to the S-trains, but at several stations it is possible to change to the S-trains and regional trains. Consequently, the metro network and the S-train network are combined the major part of the public transport network in the Greater Copenhagen Area.

Contrary to the S-train network, the metro network does not have a fixed timetable but is defined as specific time intervals between the trains depending on the time of the day. For example, during peak hours 07.00-09.00 AM and 02.00-06.00 PM the interval will be 2 minutes on the central part of the lines M1 and M2 from Vanløse to Christianshavn and 4 minutes on their radial lines towards Vestamager and Copenhagen Airport. In other hours, the interval is increased.

2.4 Other railway lines

In this project, other railways refer to heavy railways/long-distance trains (regional- and intercity lines) as well as the local train network in Northern Zealand and from Køge towards Rødvig and Faxe Ladeplads.

The regional train network in the Greater Copenhagen Area is a parallel network to the S-train network. These systems are in general isolated from each other, but at some few stations there is a connection from the S-train infrastructure to the regional train network—these are, however, not used in normal operation. All regional trains are operated by DSB and for the trains towards Sweden in collaboration with Swedish railway companies.

At some stations in the S-train network, it is possible to change to the regional train or long-distance intercity trains. The regional train service has several different systems and timetables and can be illustrated as both a commuter service and long-distance regional trains. The network is illustrated in Figure 7.

![Figure 7: The regional train network in the capital region. The lines are illustrated in green and important stops, such as stations which also are S-train stations, are also illustrated.](image-url)
In Figure 8, a map showing the regional train lines and their stations is illustrated.

Furthermore, the local train service in Northern Zealand as well as to the south of Køge is also important for the S-train system since these lines connects the S-train network to other towns and cities from where passengers might commute towards Copenhagen. The different lines are operated by the railway company Lokaltog – the transport service organisation is, however, Movia (Ingvardson, 2019). The lines in Northern Zealand are the following (with line number):

- **Nærumbanen (910):** Jægersborg-Nærum (every 20 min, during rush hour every 10 min)
- **Frederiksværkbanen (920R):** Hillerød-Frederiksværk-Hundested (every 30 min and with a fast train every hour)
- **Lille Nord (930R):** Hillerød-Helsingør (every 30 min)
- **Hornbækbanen (940R):** Helsingør-Hornbæk-Gilleleje (every 30 min)
- **Gribskovbanen (950R/960R):** Hillerød-Gilleleje/Tisvildeleje (every 30 min)

Two local train lines have their northern terminus at Køge. These are:
- **Østbanen (110R/210R):** Køge-Hårlev-Faxe Ladeplads/Rødvig (every 30 min)

A map with the lines is illustrated in Figure 9.

![Figure 9: Overview of local train lines as adjacent networks to the S-train network.](image)

### 2.5 Buses
The bus network in the Greater Copenhagen Area is also included for the route choice calculation in this project. The bus network consists of different lines among several categories such as A-buses, S-buses and the regional R-buses. The primary focus, however, in this project is the railway systems which means that the bus network is mentioned only briefly.
2.6 Planned extensions of the network

In order to determine the potential for an extension of the S-train network in the future, it is necessary to make clear how the planned future public transport network will be developed. For this purpose, the following current projects under construction and further planned projects within the Greater Copenhagen Area and in its surroundings are described in detail in this chapter. Only projects, which are mentioned in the report “Trafikplan for den statslige jernbane 2017-2032“, are assumed to be adopted and implemented. However, a few other projects which could have an influence for the S-train network are also mentioned briefly.

2.6.1 Trafikplan 2032

The report “Trafikplan for den statslige jernbane 2017-2032” presents the different upcoming projects for the state-owned railways and stations in the upcoming years. The projects include in general new railway lines, upgrading of existing railways as well as new stations. Furthermore, the expected development in the number of passengers and passenger kilometres is also presented in the light of the future train service in 2022, 2027 and 2032 (Danish Transport, Construction and Housing Agency, 2017). The report presents the upcoming projects for the entire country including new regional service in other parts of Denmark as well as new intercity service, but since this project is limited to the capital region, only the projects concerning the capital region are introduced.

2022:
• The new line between Copenhagen and Ringsted is opened
• New regional train service Copenhagen-Køge-Næstved
• The operator Lokaltog operates the regional trains/local trains from Roskilde to Køge and towards Faxe Ladeplads and Rødvig

The following traffic plans inherits the same projects and present new ones.

2027:
• Ring Syd is introduced - two regional trains run towards Ny Ellebjerg and Copenhagen Airport instead of Copenhagen Central Station (this includes new platforms on Ny Ellebjerg Station)
• The train service Kystbanen is separated from the train service across Øresund to Sweden and is linked to other regional lines on Zealand
• The new metro line Sydhavnsmetroen is opened
• The new light rail line on Ring 3 is opened

2032:
• New Fehmarn Fixed Link is opened to the public.
2.6.2 S-train network

Currently, no new lines or extensions of the network are decided according to the report “Trafikplan for den statslige jernbane 2017-2032”. However, the S-train network is in the upcoming years undergoing change. First of all, new stations will be constructed and implemented and the newest station is Køge Nord, which was finished and opened in May 2019 when the new Copenhagen-Ringsted line was opened.

Furthermore, two new stations are decided and will undergo construction in the following years. These are:

**Vinge:** The station will be located in Frederikssund Municipality. This station will serve the new town Vinge which will be developed in the upcoming 10 years and the population is estimated to 10,000-20,000 inhabitants (Frederikssund Kommune, 2019). The new station will be located at the Frederikssund-branch (see Figure 10) and served by the lines C and H. The station is expected to be opened in summer 2020 (Banedanmark, 2019).

Vinge Station was mentioned in the report “Optimering af stationsstrukturen” from 2014 by the Danish Transport Agency (today Danish Transport, Construction and Housing Agency). At this time, an estimated number of 450 passengers on a normal weekday was the basis. However, this number of passengers is considered to be “very low” for an S-train station, but the report states a potential for opening the station provided that the urban development is continued and since the capacity consumption on the line is not critical.

This station is also included in LTM.

**Favrholm:** The upcoming Favrholm Station will be located in Hillerød Municipality south of Hillerød. This will serve the new hospital close to the station and the S-trains on line A as well as the local railway towards Frederiksværk and Hundested will stop at the station (see Figure 11).

Furthermore, Favrholm Station should also contribute to urban development in the southern parts of Hillerød as well as being an ideal station for commuters (Banedanmark, 2019). The report “Optimering af stationsstrukturen” estimated a number of passengers of 1,100 on a normal weekday. In this report, Favrholm is named “Hillerød Syd”.

![Figure 10](image1.png) Location of Vinge Station between Frederikssund and Ølstykke along the Frederikssund line.

![Figure 11](image2.png) Location of Favrholm Station between Hillerød and Ølstykke along the Frederikssund line.
The station is expected to be opened in 2021 and the new hospital in 2022. Hence, it will be included in the analysis since it is already included in LTM.

Two more locations are mentioned as a potential for new stations. The first one is Priorparken in Brøndby Municipality which is located at the industrial parks Priorparken and Vibeholm. This new station will then be located between the existing stations Brøndbyøster and Glostrup. Hovedstadens Udviklingsråd (HUR) concluded in 2003 that this area had good development opportunities and there should be a potential for a new station. The report “Fingerplan 2013” also listed this station as a new station for S-trains. However, there are no plans for the establishment of this station (Glostrup Kommune, 2015). Likewise, the report “Optimering af stationsstrukturen” states, that this station cannot be recommended until an urban development in this area will be established, even though that the station was considered to get 2,500 passengers on an average weekday (Danish Transport Agency, 2014).

The other station is Trylleskov Strand in Solrød Municipality. This station will be located in the new urban area Trylleskov Strand and according to the municipality the line towards Køge is already prepared for a new station. Currently, the station is not decided since the decision will be adopted in 2020 at the earliest (Solrød Kommune, 2018) and the exact location is unclear. Furthermore, the number of daily passengers on an average weekday was in 2014 estimated to 550 which is a low number for an S-train station (Danish Transport Agency, 2014).

Since both stations are not decided or included in LTM they will not be included in the analysis.

Furthermore, the S-train network is currently undergoing a major change; the existing signalling system and ATP-system HKT (“Hastighedskontrol og Togstop”) (Landex, Rail Traffic Engineering - Spring 2014, 2014) will be fully replaced by the new signalling system CBTC (“Communication Based Train Control”) because the existing signals and interlocking systems are old (Banedanmark, 2019). The new CBTC-system is at the present moment in operation on the lines (Svanemøllen)-Hellerup-Hillerød and Ryparken-Hellerup-Klampenborg. The line Jægersborg-Hillerød was the first line with the CBTC-system in operation in 2016 and the lines (Svanemøllen)-Hellerup-Jægersborg and Ryparken-Hellerup-Klampenborg followed in May 2019. It is expected that the roll-out of CBTC on all lines will be completed in 2021/2022 with the lines Carlsberg-Frederikssund/Høje Taastrup as the final parts (Banedanmark, 2018). Therefore, the signalling system in possible extensions of the network will be based on this technology and it is assumed that the roll-out is already completed before extensions are established. The technology behind CBTC will be elaborated in chapter 4.5.
2.6.3 Metro lines
The newest line in the Copenhagen metro network is Cityringen which was opened to the public September 29th, 2019. Furthermore, the new line M4 to Nordhavn with the terminus Orientkaj will be opened in the beginning of 2020 (Metroselskabet I/S, 2019). In 2024, the new line Sydhavnsmetroen between the metro station at Copenhagen Central Station and Ny Ellebjerg will be finished. This line will be an extension to the line Nordhavnsmetroen, M4, from Copenhagen Central Station to Orientkaj. The new line will be constructed with five new stations:
- Havneholmen
- Enghave Brygge
- Sluseholmen
- Mozarts Plads
- Ny Ellebjerg (terminus)
The new metro line, which is illustrated in Figure 12 below, is expected to get 29,000 daily passengers in 2035. On a yearly basis, it corresponds to 9m passengers (Metroselskabet I/S, 2018).

Furthermore, new plans are currently going on for extending the metro network to new locations outside Copenhagen and Frederiksberg as well as Tårnby Municipality on Amager. 11 municipalities in the environs of Copenhagen suggest a new line to Rødovre with expected 30,000 passengers on an average day as well as a new line from Vanløse to Herlev (Omegnskommunerne, 2018).
Another line towards Lynetteholmen, a possible new urban area at Prøvestenen, was proposed by the previous government in 2019 in its proposal for the future development of the capital. Here, it was proposed that Nordhavnsmetroen could be extended to Lynetteholmen or at least a feasibility study of the new line should be investigated (Regeringen, 2019). In the meantime, the municipality of Copenhagen suggests a line from Copenhagen Central Station to Refshaleøen with an extension towards Lynetteholmen (Bindkilde, 2018).

Even more lines have been investigated by Metroselskabet: The report “Forlængelse fra Ny Ellebjerg” mentions a metro or a light rail line towards Hvidovre Hospital and Bispebjerg Hospital with Ny Ellebjerg Station as the starting point (Metroselskabet I/S, 2019) as new extensions.

It can be concluded that there are many plans for extending the metro network in Copenhagen at the current moment. However, the new lines from the report by Metroselskabet are not decided yet and since the report is based on a screening, it is considered that there is a high uncertainty about the alignment as well as the number and location of stops. Hence, in this analysis the new lines will not be included but when the decision about new extensions of the S-train network is going on, it might be necessary to include them in further analyses.

### 2.6.4 Light rail

In 2025, a new transport mode is implemented in the network of public transport in the Greater Copenhagen Area: Light rail. The light rail line, Hovedstadens Letbane, will operate between Lyngby and Ishøj with Lundtofte and Ishøj Station as termini. The line itself has a length of 28 km and the main part of its alignment will be constructed along the orbital road Ring 3. The map in Figure 13 illustrates the alignment and location of stops.

Furthermore, 29 stations will be constructed along the line and the headway will be 5 min between departures in daytime on weekdays and 10 min in evening and on weekends (Hovedstadens Letbane, 2015). Since this project already is undergoing construction, it is also included in LTM and therefore included in route choice analyses.
Another line, that might be established in the future, is a light rail line from Nørrebro Station to Gladsaxe Trafikplads. At Nørrebro Station it is possible to change to the S-train line F as well as the new metro line Cityringen (M3), and at Gladsaxe Trafikplads it is possible to change to the upcoming light rail line along Ring 3 (Københavns Kommune, Gladsaxe Kommune and Region Hovedstaden, 2018). But since this project currently is based on a screening and the alignment and stations are not decided yet, it is decided to not include this project in the analysis.

### 2.6.5 New railway lines

Two new railway projects will probably be conducted in the upcoming years. The first project is Ring Syd which makes it possible to schedule direct regional trains from Roskilde as well as intercity trains from western parts of Denmark to Copenhagen Airport via Ny Ellebjerg Station. Furthermore, it will also be possible to reroute the trains towards Copenhagen Airport instead of Copenhagen Central Station. The main purpose is to reduce the travel time for passengers travelling from the western parts of the Greater Copenhagen Area instead of changing at Copenhagen Central Station.

The basis for this plan is to establish new platforms at Glostrup Station for regional trains. Thus, the passengers can change to S-trains, the new light rail line along Ring 3 as well as several bus lines. New platforms for trains towards the airport at Ny Ellebjerg Station were funded in 2018 (Transport-, Bygnings- og Boligministeriet, 2019). The basis for
decision by Banedanmark from 2017 lists different scenarios for implementing Ring Syd depending on number of new platforms for regional trains at the stations Glostrup and Ørestad. This is illustrated in Figure 14 below.

![Figure 14: Overview and alignment for Ring Syd as proposed by Banedanmark.](image)

No public timetables are published for Ring Syd at the present moment and in order to assume the train service in this system the timetables in the National Transport Model are studied. Hereby, it can be confirmed that two regional train services every hour are operated to Copenhagen Airport via Ny Ellebjerg: One line from Holbæk and Roskilde and one line from Ringsted via Roskilde. It means that a train runs between Copenhagen Airport and Roskilde every 30 minutes in both directions. However, these trains do not stop at Glostrup Station even though it is mentioned in the overview map from Banedanmark.

At the terminus for line A in the S-train network, Hillerød, another project might be implemented in the upcoming years. In collaboration with DSB, Lokaltog, Movia, Hillerød Municipality, the Capital Region of Denmark and the Ministry for Transport and Housing, Banedanmark has started an analysis about rebuilding Hillerød Station (Thygesen, 2019). With the reconstruction, the platform tracks for Frederiksværken will be connected to the platform tracks for the lines Gribskovbanen and Lille Nord, and as a result it will be possible to run the local trains directly to the new hospital at Favrholm Station (Banedanmark, 2017). Since the project is undergoing an analysis it is not determined yet how the station will be reconstructed and a new timetable is not presented. Hence, the project is not included in
this analysis, but it should be investigated when the decision for the future track layout as well as timetable has been conducted.

2.6.6 New bus network
Because of the new metro line, Cityringen, which was opened to the public September 29th, 2019, the bus network in several municipalities in the Greater Copenhagen Area is changed to the new network named *Nyt Bynet*. This new network is adapted to the new extended metro network and 33 bus lines got new route or were discontinued and replaced by other routes (Din Offentlige Transport, 2019).

For this project, the new bus network should be implemented in the assignment model in order to create the most realistic public transport network with an S-train extension. However, this network is not included in the National Transport Model (LTM) and since it would be time consuming to digitalise the new bus network in the model, it has been decided not to include this network and keep the previous network which is included in LTM. Therefore, *Nyt Bynet* is not handled in this project.

3 New tunnel for S-trains
This chapter investigates the introduction of the primary element of the study in this project: The extension of the S-train network. The chapter is introduced with an explanation of the applied method to this part and it will also introduce the analysis for concluding the need for an extension of the network. Furthermore, the chapter introduces the idea behind the specific alignment and the two alternatives in the study.

3.1 Method
The evaluation for the need is based on four main factors: Forecast for population development and development in road traffic, current and future capacity consumption in the S-train network, data about delays in the S-train network and travel time reductions from other projects. These factors are selected since they all together demonstrate that one S-train tunnel is a bottleneck for the network. With the population forecasts it will be demonstrated that the populations in the municipalities are growing which will result in a higher demand for transport towards Copenhagen if the passengers commute towards the city centre. The population forecasts are based on data from Statistics Denmark which has data about population forecasts for all municipalities in Denmark.

Another primary measurements in this chapter to investigate the need for an extension of the network is the *capacity consumption* which is introduced in this chapter. The capacity consumption *before* the extension will be evaluated in two steps:

1. The capacity consumption in the existing Boulevard Tunnel between Østerport and Copenhagen Central Station is evaluated before the roll-out of the new signalling
system CBTC. This is done on basis of literature that investigates the capacity consumption with the existing signalling system in the Boulevard Tunnel, HKT.

2. The capacity consumption after the roll-out of CBTC is also investigated. This procedure, in combination with the so-called UIC 406-method, is applied to a model in RailSys which includes the existing infrastructure in the S-train network. The S-train network is in this case divided into different sections since these sections are characterised with skip-stop-service. One example is the line Hellerup-Hillerød which is divided into the sections Hellerup-Holte and Holte-Hillerød.

It is considered that the UIC 406 method is a reliable method for investigating the future capacity consumption since it is well defined and already used by Banedanmark to investigate capacity consumptions and identify bottlenecks in the railway network.

The data about delays in the S-train network are provided by DSB which is the operating company for the S-trains. The data illustrates all registered incidents on all stations if the incident caused a delay or a cancellation. This data is investigated in order to demonstrate that incidents are likely to occur in the network and especially on the central part Dybbølsbro-Svanemøllen. Furthermore, it will also be investigated if incidents with signalling and interlocking failures in the network still are a major cause for delays and if the new signalling system will remove the majority of the delays.

Since the delays and cancellations are caused by several kinds of incidents, it is chosen to present the four kinds of incidents which account for the majority of the delays and cancellations.

Finally, a suggestion for a new S-train tunnel is based on a proposal from Ekspresgruppen who suggests a specific alignment for an S-train tunnel. It is chosen to adopt this proposed alternative for the primary element in this report’s investigations. It means that the scope and purpose of this report are not about designing the optimal alignment for a new S-train tunnel but to investigate and compare two proposed alternatives. It is also considered that the proposed alignment for a new tunnel compromises the other investigations in this chapter.

### 3.2 The need for more trains

The existing line between Dybbølsbro and Svanemøllen is today one of the primary characterisations the S-train network in the Greater Copenhagen Area since all lines except line F run through this central part. As it will be demonstrated in chapter 3.3, the current capacity consumption on the central part during peak hours is very high and exceeds the recommended limit.

The maximum number of 30 S-trains through the central part of the network is therefore considered as to be reached. However, this limit has actually been reached for many years which is illustrated in Figure 15.
Figure 15: Number of trains on the suburban tracks (the current S-train tracks) in central Copenhagen during peak hours (Landex, 2014).

Figure 15 illustrates that the number of 30 trains per hour in each direction during peak hours was actually reached in the middle of the 1980s. However, the number was later reduced due to works with, among other things, the first metro lines and an upgrade of HKT (Landex, 2014). "Other trains" until the end of the 1960s were replaced by the electric S-trains since the remaining lines in the S-train network were electrified.

With the metro lines, the high number of S-trains in the central part forms and will continuously form a high-headway network of public transit trains in the municipalities of Copenhagen and Frederiksberg. In the future, the demand for transport is expected to grow since the population in both municipalities is growing. In the upcoming 25 years it is expected that the growth in the population in Municipality of Copenhagen will increase by 20%, and in Frederiksberg a growth by only 5% is expected. This is illustrated by the graph in Figure 16.

Figure 16: Population measurement and forecast for the municipalities of Copenhagen and Frederiksberg (Statistics Denmark, 2019). 2019 is chosen as the basis year.
In the meantime, the population in the other municipalities in the capital region is also growing which also contributes to the need for a higher capacity since new inhabitants in the municipalities along the S-train radial lines might commute towards the central parts of Copenhagen. Therefore, the forecast for the future development has been analysed. For both purposes, data about the population forecast from Statistics Denmark have been applied to this investigation with the year 2019 as the base.

The first investigated branches are the Hillerød-branch (Nordbanen) and the Klampenborg-branch. The reason for this combination is that the line from Hellerup towards Klampenborg is short and is situated in Gentofte Municipality with Klampenborg Station close to Lyngby-Taarbæk Municipality. The municipalities of Gribskov, Halsnæs and Fredensborg, which are not directly served by the S-trains, are also included since the local train network have Hillerød as the terminus. The results are observed in Figure 17.

![Population forecast for the Hillerød and Klampenborg radials (index, 2019=100)](image)

**Figure 17:** Population measurement and forecast for the lines towards Hillerød and Klampenborg between 2008 and 2045 (Statistics Denmark, 2019).

From Figure 17 it is observed that no significant increase for the municipalities Gentofte, Gribskov, Lyngby-Taarbæk and Rudersdal is expected. However, a significant increase is expected for Allerød, Hillerød and Fredensborg in the northern end of Nordbanen which means that the demand for transport towards Copenhagen might be higher in the future. Both lines are included since Gentofte also includes the line to Klampenborg.

For the line from towards Farum, a similar development is illustrated in Figure 18.

![Population forecast for the Farum radial (index, 2019=100)](image)

**Figure 18:** Population forecast for the Farum-branch (Statistics Denmark, 2019).
For this branch, the population in the municipalities of Furesø and Gladsaxe is expected to grow significantly. For the lines south and west of Copenhagen, the same approach has been conducted. These are presented in Figure 19, Figure 20 and Figure 21 respectively.

**Figure 19:** Population forecast for the Frederikssund-branch (Statistics Denmark, 2019).

**Figure 20:** Population forecast for the Høje Taastrup-branch (Statistics Denmark, 2019).

**Figure 21:** Population forecast for the Køge-branch (Køgebugtbanen), (Statistics Denmark, 2019). The municipalities of Stevns and Faxe are also included since the local train from Rødvig and Faxe Ladeplads has its current terminus in Køge.
In the light of the three previous figures, it can be concluded that the population in the municipalities along the Frederikssund-branch is not expected to grow as significantly as for the branches towards Høje Taastrup and Køge. In general, it can be concluded that the population is growing in municipalities in the central parts of Copenhagen, but also significantly in the suburbs and other cities along the radial lines.

In order to determine a need for more trains in the S-train network, the development of the operation of the S-train network has been investigated. In this case, the operation is investigated from two different perspectives: The transport provided by the operator (DSB) and the number of transported passengers. The provided transport by the operator is illustrated as the measurement S-train movements in the unit 1000 train km. The measurement “1000 train km” indicates that one train has travelled the distance 1000 km or 1000 trains have travelled 1 km.

The same terminology applies to the term “Passenger km” which indicates how many kilometres the passengers have covered in the S-trains in the specified year. As Figure 22 illustrates, the number of passengers or at least passenger transport has been increasing in the years 1990-2018 even though that the amount of passenger km dropped by almost 200 m. passenger km until 2008. The figure also illustrates that the service provided by DSB has been increasing from 1990 to 2018.

![Development in S-train transport](image)

**Figure 22:** Development in S-train transport 1990-2018 and a forecast for the years 2022, 2027 and 2032 (Statistics Denmark, 2019), (Danish Transport, Construction and Housing Agency, 2017).

Figure 22 also illustrates a forecast for the amount of passenger km in the years 2022, 2027 and 2032. These years are selected, since they are presented as basis years in the report “Trafikplan for den statslige jernbane 2017-2032”. This report describes that the S-train service is expected to be almost unchanged in the upcoming years and the amount of passenger km in the years 2022, 2027 and 2032 will only be increased by 4% since 2015. The only change in the S-train network itself will be the opening of the new stations Køge Nord, Favrholm and Vinge. In the meantime, it is expected that the S-train network will benefit from the new light rail line in Ring 3 with new passengers, but other passengers will use the new metro lines and new regional train lines via the new high-speed line Copenhagen-
Ringsted instead of S-trains. The overall assumption is, that the passenger load in the S-train network will stall.

By comparison, a rapid development is observed for the annual average daily traffic (AADT) for the main motorways in the Greater Copenhagen Area in Figure 23.

![AADT on specific main roads in Greater Copenhagen Area (1988-2018)](image), Figure 23: Annual average daily traffic (AADT) for specific motorways in the Greater Copenhagen Area for the years 1988-2018 (Statistics Denmark, 2019).

It is observed in Figure 23 that the annual average daily traffic in general has increased on all motorways in the years 1988-2018. Especially the orbital road Motorring 3 has experienced a particularly rapid increase from the years 2010 to 2018 by almost 50%. It means that the transport demand has increased rapidly during the last 20 years, and the Danish Road Directorate predicts an annual increase in vehicle kilometres on Danish motorways by 0.9% for the years 2020-2030 (The Danish Road Directorate, 2019).

Hence, even though that the amount of passenger km in the S-train network has increased in the last 18 years the increase in the traffic on the main roads in the Greater Copenhagen Area has increased by a higher rate. And since the service in the S-train network and hereby in the suburbs along the radial lines in general is assumed to be at almost standstill in the upcoming years, it can be expected that the traffic will increase on the roads with possible more congestion. To avoid this, the S-train network might need to improve the service along the radial lines.

### 3.3 Capacity consumption in the S-train network

One of the most important measurements to be considered in connection to the number of trains on a certain railway line is the capacity consumption. It is important to mention the term “consumption” because the term capacity as such does not exist since the infrastructure capacity on railways depends on the way it is utilised (UIC, 2004). It means that the “capacity” depends on e.g. the speed of the trains and the number of stops. If a railway is designed for a speed limit of 160 km/h then the capacity consumption will be higher if some of the trains run with only 120 km/h. The capacity consumption is an
important measurement for describing the impacts of the current or future timetable or if the railway line needs an extension of the infrastructure.

In general, there is a correlation between four quantities when the utilisation of a railway line has to be described. These are the number of trains, the average speed, the heterogeneity and the stability of the traffic. This correlation is illustrated in Figure 24.

![Figure 24: Correlation between average speed, the number of trains, stability of the timetable and heterogeneity (UIC, 2004).](image)

According to Figure 24, the utilisation of a railway line can be divided into two classifications: A metro-train system and mixed-train service. Since the S-train network in general have a lower speed than long-distance trains as well as homogenous operation, the S-train system fits to the metro-train classification. The only difference is that the radial lines have skip-stop-service which increases the heterogeneity, raises the average speed but decreases the stability. Furthermore, the lower number of trains raises in this case the capacity consumption. It means that a lower number of trains on a specific line can have a higher capacity consumption than a line with more trains.

For calculating the capacity consumption on a specific railway line, the International Union of Railways (UIC) has developed a standardised method. In 2004, UIC published a guideline with this method, the UIC 406-method, which is suitable for calculating the consumption on lines or line segments as well as for notes or stations. The aim of this method is to develop a standard for different railway networks. The method illustrates a compression of the timetables for the trains on a specific railway line in a specified time interval. The compression is carried out until the minimum headway time between the trains in the specified time interval is reached (UIC, 2004). This method for calculating the capacity consumption is also applied for urban transit networks such as the S-train network and, therefore, it will be used in this project.
The capacity consumption according to the UIC 406-method on a specific railway line is calculated with the following formula:

\[ K = \frac{k}{U} \times 100\% . \]

In this formula, \( K \) represents the capacity consumption on the specific line as a fraction of the total consumption time (in minutes), \( k \), and the chosen time window, \( U \) (likewise in minutes). In general, the time window can vary, but it is often defined as 1 hour or 60 minutes.

The UIC 406-method applies to double-track and single-track lines. Since the whole S-train network consists of double-track lines except the segment Fiskebæk-Farum, the method will be demonstrated and evaluated on double-track lines. In such cases, one track is used for one direction and the other track for the other direction\(^1\). This means that the timetable is compressed for one direction only and the capacity consumption for the oncoming trains will then be calculated for the other track.

When the capacity consumption has to be evaluated, UIC has suggested different levels for the maximum capacity consumption on railway lines, depending on the classification of these. In general, railway lines can be divided into three main types as illustrated in Table 2 below (Landex, Capacity Statement for Railways, 2007).

<table>
<thead>
<tr>
<th>Type of railway line</th>
<th>Peak hour</th>
<th>Daily period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dedicated suburban passenger traffic</td>
<td>85%</td>
<td>70%</td>
</tr>
<tr>
<td>High-speed lines</td>
<td>75%</td>
<td>60%</td>
</tr>
<tr>
<td>Mixed-traffic lines (heterogeneous operation)</td>
<td>75%</td>
<td>60%</td>
</tr>
</tbody>
</table>

Table 2: UIC’s suggestions for maximum capacity consumption.

Since the S-train network is a suburban passenger train network, the first type applies to the investigation of the capacity consumption.

The S-train network is today characterised with the bottleneck between Svanemøllen and Dybbølsbro since all S-train lines except line F are running via this line from the northern radial lines to the southern radial lines. During rush hour, the line Svanemøllen-Østerport has 27 S-trains in each direction per hour, whereas Østerport-Dybbølsbro are used by 30 trains in each direction every hour since line H has its terminus at Østerport – according to the timetable S20. The S-train network is undergoing a change from the system HKT to the new signalling system CBTC which is currently in operation on the lines (Svanemøllen)-Hellerup-Hillerød and Ryparken-Klampenborg. However, HKT is still in operation on the line Svanemøllen-Dybbølsbro and the existing number of trains in the bottleneck results in a capacity consumption by up to 90% on a daily basis (Landex & Wellendorf, Fremtidens S-bane i København, 2008).

In this project, it is assumed that CBTC is rolled out on all S-train lines when new extensions are established. The capacity consumption for the S-train network after the roll-

\(^1\) Bidirectional operation on both tracks might, however, be an option.
out of CBTC will be calculated by using RailSys, which uses the UIC 406 compression method. For the timetable S20 on the S-train network with CBTC, the capacity consumptions are listed in Table 3.

<table>
<thead>
<tr>
<th>Railway line</th>
<th>Capacity consumption (northbound)</th>
<th>Capacity consumption (southbound)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Svanemøllen-Dybbølsbro</td>
<td>71.8%</td>
<td>70.3%</td>
</tr>
<tr>
<td>Dybbølsbro-Valby</td>
<td>36.0%</td>
<td>33.1%</td>
</tr>
<tr>
<td>Dybbølsbro-Hundige</td>
<td>76.2%</td>
<td>75.0%</td>
</tr>
<tr>
<td>Hundige-Køge</td>
<td>19.4%</td>
<td>18.1%</td>
</tr>
<tr>
<td>Valby-Glostrup</td>
<td>30.7%</td>
<td>25.5%</td>
</tr>
<tr>
<td>Glostrup-Høje Taastrup</td>
<td>19.8%</td>
<td>18.2%</td>
</tr>
<tr>
<td>Valby-Ballerup</td>
<td>40.4%</td>
<td>40.9%</td>
</tr>
<tr>
<td>Ballerup-Frederikssund</td>
<td>22.0%</td>
<td>17.5%</td>
</tr>
<tr>
<td>Svanemøllen-Buddinge</td>
<td>19.6%</td>
<td>18.4%</td>
</tr>
<tr>
<td>Buddinge-Farum</td>
<td>18.4%</td>
<td>16.0%</td>
</tr>
<tr>
<td>Svanemøllen-Hellerup</td>
<td>20.3%</td>
<td>21.5%</td>
</tr>
<tr>
<td>Hellerup-Holte</td>
<td>75.2%</td>
<td>71.8%</td>
</tr>
<tr>
<td>Holte-Hillerød</td>
<td>16.9%</td>
<td>17.2%</td>
</tr>
<tr>
<td>Hellerup-Klampenborg</td>
<td>13.8%</td>
<td>13.3%</td>
</tr>
<tr>
<td>Hellerup-Ny Ellebjerg</td>
<td>27.0%</td>
<td>30.0%</td>
</tr>
</tbody>
</table>

Table 3: Capacity consumption for different lines in the S-train network after roll-out of CBTC.

The capacity consumptions in Table 3 are based on timetable S20 in RailSys during peak hours 07:00-09:00. For the line Dybbølsbro-Valby-Høje Taastrup, northbound is used for eastbound trains and southbound for westbound trains.

From Table 3 it is observed that the capacity consumption during peak hours on the central part of the network between Svanemøllen and Dybbølsbro does not exceed the limit of 85% capacity consumption during peak hours according to UIC’s suggestions. It means that the current number of trains on the central part of the network is not critical when CBTC is rolled out.

Furthermore, it is also observed that the radial lines except the lines Hellerup-Holte and Dybbølsbro-Hundige have a low capacity consumption. Please notice that the capacity consumption for Buddinge-Farum seems to be low. The single-track line from Fiskebæk to Farum decreases the capacity significantly – this is further mentioned in chapter 5.

These capacity consumptions agree with the claim in the report “Trafikplan for den statslige jernbane 2017-2032” that it should be possible to shorten the headway between the S-trains on the central part of the network benefitting from the new signalling system. It is mentioned that up to 36-39 S-trains in each direction through the central part of the network is possible. According to the measurements in RailSys, the lines Hellerup-Holte and Dybbølsbro-Hundige will still experience a high capacity consumption which means that CBTC does not decrease the capacity consumption noticeably.
3.4 Incidents and their impact on other lines

Even though that the capacity consumption on the central part of the S-train network might be decreased in the future as a benefit from the new signalling system, the shortcoming is still that all lines except line F have to run through the same link from the northern radial lines towards Frederikssund, Høje Taastrup and Køge. It means that if an incident happens at the stations at the central part, all lines will with a high probability be affected by it unless some lines are reversed at e.g. Svanemøllen or Copenhagen Central Station before entering the same double-track via the central stations. For investigating the number of incidents in the central part of the network, a data list from DSB about causes of delays and cancellations for the S-trains has been conducted. This dataset includes a categorisation of the causes as well as the number of affected trains and the number of affected arrivals. Moreover, the dataset also includes the station at which the incident occurred. For the investigation of the incidents in the central part, a grouping of incidents at the stations Svanemøllen, Nordhavn, Østerport, Nørreport, Vesterport, Copenhagen Central Station and Dybbølsbro has been arranged. The results can be observed in Figure 25. A delay in this dataset is registered when an S-train is more than 2 minutes delayed.

In Figure 25 it is illustrated that the most frequent incident in the central part, which causes the affected arrivals in the entire network, is interlocking and signalling failures. For the years 2013-2018 this has been the case for approximately 50% on average where the only exception is the year 2018. Hence, the majority of the causes is the interlocking and signalling failures. It means that a huge part of the delays and cancellations can be prevented if the number of failures in the interlocking and signalling systems on the railway can be reduced. Banedanmark expects that up to 50% of these failures with the current HKT-system can be reduced when it is replaced by the new CBTC-system.
Consequently, 25% of the total number of causes can be removed with the new system. The following causes are vandalism, track defects and collision with persons. Vandalism refers to, among other things, graffiti, smashed windows in the trainsets and passengers pulling the emergency brake. In average, these causes count for 5%-10% of the affected arrivals, and especially personal collisions are an important factor. The number of incidents from personal collisions is very small, but since this cause has an enormous influence on the number of the affected trains it has a high share in Figure 25. Other categorised causes such as defects on the trainsets or staff related causes do also apply to this statistic, but since these have a small share of the total number of incidents, they are omitted from the figure. In general, it can be concluded that the reduction of interlocking failures will have a high influence on the reliability since this cause accounts for a high share of incidents. But since these failures would be removed by 50%, signalling and interlocking failures – as well as the other incidents – will still be accountable for many delays. It means that a new signalling system will not solve all problems. Furthermore, it has also been investigated where the majority of the incidents in the entire network happens from where the majority of the delayed arrivals and cancellations occurs. The results are illustrated in Figure 26 below.

Figure 26: Delayed and cancelled arrivals caused by incidents at stations in the S-train network. Stations with no data are Køge Nord, Vinge and Favrholm since these are not included in the statistics.
Figure 26 illustrates that the majority of the delayed and cancelled arrivals are caused at terminus stations like Køge, Holte and Hillerød and especially the central part from Dybbølsbro to Svanemøllen and Hellerup. Moreover, the stations which cause more than 100,000 delayed and cancelled arrivals are Copenhagen Central Station and Østerport. It means that delays from the stations in the city area of Copenhagen will spread to other parts of the network.

Incidents, which cause a delay or a cancellation, have an enormous socio-economic influence. In 2017, COWI made a report about the socio-economic costs as a consequence of train delays. In brief, the result was that train delays in Denmark cost 2.4 billion DKK every year, from which 701 million DKK are from delays in the S-train network (COWI, 2017). This can be compared with the stations on the central part of network and their share of the total train delays and the results from this investigation are listed in Table 4 below.

<table>
<thead>
<tr>
<th>Year</th>
<th>Share of all delays in the network from the central part</th>
</tr>
</thead>
<tbody>
<tr>
<td>2013</td>
<td>36.2%</td>
</tr>
<tr>
<td>2014</td>
<td>39.6%</td>
</tr>
<tr>
<td>2015</td>
<td>40.2%</td>
</tr>
<tr>
<td>2016</td>
<td>35.4%</td>
</tr>
<tr>
<td>2017</td>
<td>38.7%</td>
</tr>
<tr>
<td>2018</td>
<td>41.0%</td>
</tr>
<tr>
<td>Average</td>
<td>38.5%</td>
</tr>
</tbody>
</table>

Table 4: Share of all delays in the network from the stations Svanemøllen, Nordhavn, Østerport, Nørreport, Vesterport, Copenhagen Central Station and Dybbølsbro.

It means that the delays and cancellations caused by incidents in the central part of the network has a high impact of the socio-economic statement if 38.5% in average of the delays could be significantly reduced. On the other hand, if an incident like a personal collision happened in the bottleneck and an alternative tunnel existed, the trainsets could use the alternative and not be affected by it.

3.5 Travel time and extensions in the upcoming years

According to Trafikplan 2032, the new projects for the public transport network in the Greater Copenhagen Area are the extensions of the metro networks to Nordhavn and Sydhavn, the new light rail line on Ring 3, new S-train stations and new platforms on Ny Ellebjerg Station for trains towards Copenhagen Airport. It means that the public transport network is undergoing a major extension with new lines and transport systems. Back in 2013, the commission Trængselskommissionen published a report about suggested extensions of the infrastructure in the capital region. The commission suggested in the report that the entire S-train network should be analysed in detail in combination with the
new signalling system CBTC, driverless S-trains and S-trains to Roskilde. Furthermore, the commission has also discussed the basis for a new S-train tunnel in Copenhagen via the inner parts of Nørrebro and Rigshospitalet.

In the meantime, the commission suggested only four new real upgrades of the network: S-train to Roskilde, improvement of Kystbanen to Helsingør, capacity analyses of the S-train network after roll-out of CBTC and driverless S-trains. In the meantime, the demand for transport is also assumed to be increased for other radial lines besides Kystbanen and the line to Høje Taastrup since the population in the municipalities along the S-train radial lines is increasing. The report did not suggest a specific alignment for an S-train tunnel which could have been beneficial for especially the reliability in the network as well as an increased number of passengers (Trængselskommissionen, 2013).

After the publication of the report by Trængselskommissionen, the metro line, Sydhavnsmetroen, and a light rail line on Ring 3 were decided and adopted, and currently these projects are undergoing construction. It is evaluated that the light rail line will reduce the travel time between the radial lines in the S-train network since no rail transport between the radial lines exists today. Contrary to the connections between the radial lines, a high-classed public transport is already offered from west to east with the radial S-train lines and the metro systems. Especially Cityringen and the upcoming lines to Nordhavn and Sydhavn reduce the travel time between the different urban areas in Copenhagen.

In the meantime, Cityringen as well as the new metro line do not reduce the travel time between the northern parts of the Greater Copenhagen Area and the southern parts. For instance, the travel time between the northern radial lines from Hellerup to Valby or Ny Ellebjerg will not be reduced with the new metro extensions or the light rail. Even though Ringbanen is an alternative to the tunnel via Nørreport Station, it will not be faster to change at Ny Ellebjerg and Hellerup than travelling via Copenhagen Central Station and Nørreport\(^2\). Therefore, the demand for a shorter travel time in this corridor is the basis for investigation in this project.

### 3.6 Suggestion for a new tunnel

In the light of the chapters 3.2, 3.3 and 3.4, it can be concluded that the existing tunnel have capacity left during peak hours after the roll-out of CBTC. However, since the new signalling system does not solve all problems with incidents and delays in the system, or more specifically in the tunnel, or shorter travel times to and from the city centre and between the radial lines, it can be stated that an alternative to the existing tunnel might be relevant for the S-train network.

In 2013, a report by a new interest group, *Ekspresgruppen*, commented on the same problems with the existing tunnel. Especially the long travel time for the passengers

\(^2\) According to the timetable S20 and connections between line A, E and F.
between the radial lines and from the southern parts of Copenhagen to the northern parts was the main focus. Therefore, the group suggested a new tunnel for S-trains in the central parts of Copenhagen – a so-called Express Tunnel. The original alignment – alternative 1 - as well as an alternative 2 are illustrated in Figure 27.

Figure 27: Proposed alignments for the Express Tunnel. Alternative 1 is the original proposal by Ekspresgruppen. Alternative 2 includes a station at Rigshospitalet as well.

The inspiration for this tunnel is a proposal for a similar S-train tunnel by Otto Anker Nielsen and Alex Landex, DTU, from 2007 (Koefoed & Norre, 2013). This tunnel should have an alignment from Copenhagen Central Station to Emdrup on the Farum-branch and Ryparken and Hellerup on the other northern branches. The new suggestion is a tunnel from Valby and Ny Ellebjerg by bypassing Copenhagen Central Station and the purpose of this alignment is to reduce the travel times between the radial lines in the west and
south to the northern radial lines for these passengers that do not have Copenhagen Central Station or other stations on the existing central part as their destinations. Furthermore, another purpose is to reduce the travel time from the radial lines to the metro lines which means that a reduction of travel times for more pairs of origin and destination stations should be obtained, and since many delays actually are caused by incidents at Copenhagen Central Station.

The proposed alternative for the Express Tunnel, however, does not include any new stations or service areas in Copenhagen with high-classed public transport. Therefore, the new alignment is combined with the original alignment proposed by Otto Anker Nielsen and Alex Landex since this alignment also included a station at Rigshospitalet. The benefit of adding this station is illustrated in Figure 28.

![Figure 28: Alternative 2 including buffer circles with 600 m radius.](image.png)
Figure 28 illustrates that a station at Rigshospitalet will cover a specific area, which otherwise would not be covered by S-train or metro in the inner parts of Copenhagen. Some few spots will still remain, specifically at Frederiksberg north of Valby Station, but since this area is covered by Frederiksberg Have and Zoo, it is considered as an area without many inhabitants and jobs.

Since this proposal for an alignment in Copenhagen satisfies the need for an alternative in the light of many delays, limited capacity consumption and shorter travel times, this project will be based on the investigation of an implementation of the Express Tunnel and both alternatives will be investigated for comparing these as well for discussing advantages and disadvantages with these.

4 Running time calculations and timetable
In order to formulate timetables for the S-trains in the extended network, it is necessary to calculate the running time and dwell times. The method behind the calculations will be explained in this chapter.

4.1 Method
The general method for calculating the running time and headways for the S-trains in the existing railway network as well as in the new Express Tunnel is based on the report “Metode til at fastlægge køretider på jernbanen i planlægningsprojekter” by DSB, Banedanmark and the Danish Transport Agency. This report has two purposes:

- To standardise the determination of running times between stations for rolling stock in a planning project
- To standardise the determination of dwell times at stations in a planning project

For both purposes, the term “planning project” is mentioned. In this case, a planning project refers to a future project and not a realised project which means that the realised conditions for the project are not determined and therefore uncertain. In order to deal with these factors, the method is simple and manageable and satisfy the circumstances in this project since it is not yet realised. However, if the project later should be realised and a realised timetable should be determined, this method cannot be applied to calculate the running times since a detailed analysis of the infrastructure, e.g. for bottlenecks, and rolling stock is necessary and since these factors are not included in this method. One specific premise in the method is that the running time supplement is only a minimum, and in a realised timetable it can be slightly lower or much higher for specific parts of the railway line.

The chapter introduces the elements in running time calculations as well as calculations for dwell times. Since the calculation includes more steps, all steps are mentioned and commented since these give an overview of the entire determination of the timetable for
the lines in the S-train network. The calculations throughout the project are based on the rolling stock class SA/SE.

For calculating the technical running time between the stations, it is necessary to use a dedicated software for railway timetabling. For this purpose, the software RailSys is used since this program already is used by Banedanmark for timetabling and since a basic network model for the network with CBTC already is digitalised in RailSys. However, another simpler program could be applied to the calculations, but it would require a complete digitalisation of the entire network. By applying RailSys, it is only necessary to digitalise the Express Tunnel as an addition to the existing network.

This chapter introduces the main platforms *Infrastructure* and *Timetable* in RailSys and illustrates how these are applied to the running time calculations. However, the third platform *Simulation* is not used in this project since a simulation model is rather complex and time-consuming to build up and since a simulation is out of this project’s scope. However, it would be relevant to simulate the timetable in order to test if the timetable and the usage of the infrastructure is feasible and robust. In this project it is therefore assumed that the timetable is feasible by investigating the running times and headways between the trains.

Finally, the chapter also introduces the theory behind CBTC. The reason for this is to test the theory behind the signalling system and especially the moving block configuration in RailSys.

### 4.2 Running time

For scheduling the trains in a timetable, it is necessary to calculate the running times for the trains. The running time depends on the infrastructure, the rolling stock and running time supplement. In this case, the calculations are based on the report “*Metode til at fastlægge køretider på jernbanen i planlægningsprojekter*” and the elements in calculations of running time is illustrated in Figure 29 below.

![Running time](image.png)

*Figure 29: Elements in calculation of running times.*
The running times are divided up into two main parts: The technical running time or free running time and running time supplement. The technical running time is defined as the technically possible running time between the stations and depends on the infrastructure and the rolling stock, e.g. if there is a specific speed limit on a specified part of the infrastructure as well as acceleration and deceleration performance for the specified train class. In this project, the technical running times for the SA train units\(^3\) are calculated in RailSys based on the technical specifications of the infrastructure.

Since the technical running time depends on the rolling stock, four formulas are applied to calculate the distances and times for acceleration as well as deceleration/braking. The formulas for acceleration time, \(t_{\text{acc}}\), and acceleration distance, \(d_{\text{acc}}\), are given by

\[
t_{\text{acc}} = \frac{-\ln(1 - \frac{v}{v_{\text{max}}}) \cdot v_{\text{max}}}{a_0},
\]

and

\[
d_{\text{acc}} = -\frac{v_{\text{max}}^2}{a_0} \left(\ln\left(1 - \frac{v}{v_{\text{max}}}\right) + \frac{v}{v_{\text{max}}}\right),
\]

respectively. In these formulas, \(v\) represents the target speed in m/s, which depends on the starting acceleration \(a_0\) and the theoretical maximum speed \(v_{\text{max}}\). Likewise, the formulas for deceleration time, \(t_{\text{dec}}\), and deceleration distance, \(d_{\text{dec}}\), are given by

\[
t_{\text{dec}} = \frac{v}{c \cdot 6.1 \cdot C + 61 \frac{v}{1200} + g \cdot %} + 2 \cdot t_{\text{ba}},
\]

and

\[
d_{\text{dec}} = \frac{v^2}{2 \left(c \cdot 6.1 \cdot C + 61 \frac{v}{1200} + g \cdot %\right)} + t_{\text{ba}} \cdot v,
\]

respectively. The braking properties depend on the braking ratio \(c\) and the braking percentage \(C\) as well as the gradient on the line and the gravitational acceleration \(g\). The braking application time \(t_{\text{ba}}\) is assumed to be zero for trainsets and the lines are also assumed to flat for the calculations since gradients of the line are too uncertain on an early stage. The quantities for the S-trains are listed in Table 1.

For calculating the running time supplement, the procedure in the report is based on UIC’s method for calculating running time supplements according to the report “Metode til at fastlægge køretider på jernbanen i planlægningsprojekter”. With this method it is necessary to distinguish between locomotive-hauled trains and trainsets. Since the SA-unit is a trainset the procedure will follow UIC’s methods for trainsets, and the total running time supplement consists of three parts:

---

\(^3\) In RailSys, the scheduled trains are displayed as SA units. SA and SE have the same specifications.
A) Time supplement based on the length between two stops
B) Time supplement as a percentage of the calculated technical running time
C) Supplement factor (to be determined on the basis of criteria)

Part A) states, at time supplement of 1 min per 100 km should be added. This can be done in two ways:
1) The time supplement is equally distributed on the total length
2) The time supplement of 1 min is added after 100 km
In this project method 1 is applied to the calculations. This corresponds to 60 s/ 100 km = 0.6 s/km.

Part B) adds a specified percentage of the technical running time. This supplement percentage is presented in Table 5 below:

<table>
<thead>
<tr>
<th>Speed Range</th>
<th>Supplement Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 140 km/h</td>
<td>3%</td>
</tr>
<tr>
<td>141-160 km/h</td>
<td>4%</td>
</tr>
<tr>
<td>161-200 km/h</td>
<td>5%</td>
</tr>
<tr>
<td>201-250 km/h</td>
<td>6%</td>
</tr>
<tr>
<td>&gt;250 km/h</td>
<td>7%</td>
</tr>
</tbody>
</table>

Table 5: Supplement percentage of the technical running time. This should be added to the technical running time.

Since the maximum (allowed) speed limit of the SA trainsets is 120 km/h, the value 3% is applied to the calculations.

Part C) is, as mentioned, a supplement factor. The purpose of this factor is to take a high capacity consumption and heterogeneous operations on the line into account. The factor varies between 1 and 2 and depends on if the infrastructure has a double-track, a single-track or if the timetable should be based on freight trains. The S-train network has a double-track on all lines\(^4\) so the factors for double-tracks are applied. The following factors for double-tracks are illustrated in Table 6 below.

<table>
<thead>
<tr>
<th>Situation</th>
<th>Supplement factor for double-tracks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basis</td>
<td>1</td>
</tr>
<tr>
<td>High capacity consumption</td>
<td>1.5</td>
</tr>
<tr>
<td>Heterogeneous/complex operation</td>
<td>1.5</td>
</tr>
<tr>
<td>High capacity consumption and</td>
<td>2</td>
</tr>
<tr>
<td>heterogeneous/complex operation</td>
<td></td>
</tr>
</tbody>
</table>

Table 6: Running time supplement factor for double-tracks (Banedanmark, DSB and the Danish Transport Agency, 2013).

As observed in Table 6, the factor increases if the specific line has a high capacity consumption or heterogeneous operation or both.

\(^4\) The only exception is the part Fiskebæk-Farum on the Farum-branch, but since this is very short, it is omitted for the explanation.
As illustrated in Figure 24, a high number of trains on the specified line might be a stable timetable unless it has a strong heterogeneity. In the case with the S-train network it can be stated as a homogenous network, since only the S-trains are running on the different lines in normal operation. However, the lowest headway is a 10 min headway on all lines which means that the capacity consumption is assumed to be high on all lines. As a result, the factor 1 is used when the capacity consumption is low and 1.5 when the capacity consumption is high as a consequence from skip-stop-service or a high number of trains.

4.3 Dwell time

In addition to the running time, the timetable for a train also depends on the dwell time at stations. The dwell time is defined as the time from the train has stopped until it begins accelerating and, as a minimum, this time will be an expression of the time allowing passengers to get in and out at the platforms (Landex, Rail Traffic Engineering - Spring 2014, 2014). However, the dwell time also depends on opening and closing procedures of the doors as well as other procedures. In general, the dwell time can be divided into three main groups as listed in the report “Metode til at fastlægge køretider på jernbanen i planlægningsprojekter” by Banedanmark, DSB and the Danish Transport Agency from 2013:

- Boarding and alighting time: Time for boarding and alighting passengers as well as for specific procedures
- Technical reaction time: Time for opening and closing of doors and starting of train. This time depends on the train class
- Departure procedure: Time for communication between conductor and engine driver

The S-train units have no conductor which means that there is no departure procedure between a conductor and the driver. Hence, the time for departure procedure can be neglected.

The technical reaction time depends on the type of rolling stock for the timetable. This time is defined as the time from the wheels stop rotating to the beginning of the boarding and alighting procedures as well as from the doors start closing to the wheels start rotating (Banedanmark, DSB and the Danish Transport Agency, 2013).

In the report “Metode til at fastlægge køretider på jernbanen i planlægningsprojekter”, the technical reaction time is illustrated as 8 seconds for the S-train units SA and SE. As mentioned, the boarding and alighting time also includes time for “specific procedures”. The specific procedures are in general, when the train has to reverse = change its direction or if the train unit or locomotive has to couple with other trainsets or other cars during the operation and the timetable. However, none of these procedures apply to S-trains in passenger operation, which means that additional time from such operations will not be added.
4.3.1 Boarding and alighting time

The time for boarding and alighting of passengers should be included in the dwell time. For calculating this time, it is necessary to know two factors:

- The specific train service at the station, i.e. the headway
- The number of passengers at the station

Furthermore, three more parameters are applied to the calculation of the boarding and alighting time. These are:

- Peak hour factor
- Factor for critical door
- Boarding and alighting speed

For S-trains the peak hour factor is 0.12 and the critical door factor is 0.20 for S-trains (Banedanmark, DSB and the Danish Transport Agency, 2013). Furthermore, the method assumes that the speed for boarding and alighting is 1.0 passenger per second.

The boarding and alighting time should be constant in the periodic timetable during the day which means that it depends on the number of passenger during peak hours. Hence, the number of passengers at the specific station should be known in advance and the total number of passengers during peak hours can be calculated by the following formula:

\[
\text{Total number of passengers per day} \cdot \text{Peak hour factor} = \text{Passengers in peak hour}.
\]

Afterwards, the number of passengers in the peak hour is divided by the number of departures from the station in both directions in order to calculate the average number of passengers per departure:

\[
\frac{\text{Passengers in peak hour}}{\text{Number of departures}} = \text{Average number of passengers per departure}.
\]

The next step is to multiply with the factor for critical door in the train. This results in the average number of passengers per door in the train:

\[
\text{Number of passengers per departure} \times \text{critical door factor} = \text{Passengers per door},
\]

This is divided by the boarding and alighting speed per door in the trainset. For S-trains, this number is determined to be 1.0 passenger per second. The result is the minimum boarding and alighting time:

\[
\frac{\text{Passengers per door}}{\text{Boarding and alighting speed}} = \text{minimum boarding and alighting time},
\]

---

5 The number of passengers at a station can be determined by a passenger counting.
Finally, a variation supplement is added to the previous result and this takes variations in the number of passengers into account. For calculations for S-train stations this supplement is 15% of the minimum boarding and alighting time. The final result is determined by rounding the number up or down:

\[ \text{minimum boarding and alighting time} \cdot \text{variation supplement} \approx \text{final boarding and alighting time}. \]

This method is applied to calculations of dwell times at stations in the S-train network in this project. One of the stations, at which no trains stop in the basic timetable in RailSys\(^6\), is Vinge Station. Since no passengers cannot board or alight a train at Vinge Station yet, no passenger counting has been conducted. In this case the predicted number of daily passengers at Vinge Station from the report “Trafikplan for den statslige jernbane 2017-2032” is applied to the calculations. The future number of passengers for all stations at the state-owner railway in Denmark have been predicted by the National Transport Model. The number of passengers at Vinge Station, which is estimated to 3,000, in 2022 is used as the base. This number is expected to increase in 2027 and 2032 to 4,500 daily passengers, but since the future development of Vinge and the number of inhabitants currently is uncertain (Deiborg, 2019), it has been decided to use the low number of passengers. The number of departures from Vinge Station is in the basic and scenario model determined to be 12.

For Vinge Station the boarding and alighting time would be calculated as follows:

\[
3,000 \text{ passengers per day} \cdot 0.12 = 360 \text{ in peak hour}
\]

\[
\frac{360 \text{ passengers in peak hour}}{12 \text{ departures per hour}} = 30 \text{ passengers per departure}
\]

\[
30 \text{ passengers per departure} \cdot 0.20 = 6 \text{ passengers per door}
\]

\[
\frac{6 \text{ passengers per door}}{1\text{ passenger/s}} = 6 \text{ seconds for boarding and alighting}
\]

\[
6 \text{ s} \cdot 1.15 \text{ variation factor} = \approx 7 \text{ s for boarding and alighting}
\]

To this number, the technical reaction time for the trainset should be added. With a technical reaction time by 8 seconds, the total dwell time would be 15 seconds.

\(^6\) This is further commented in section Error! Reference source not found..
This method is a rough estimate of the dwell time for a station. However, it does not take special conditions such as passengers with heavy luggage as well as entrances and exits from the station into account.

### 4.4 RailSys

In this project, RailSys is used as the software to calculate the technical running times and scheduling the timetable for the S-train scenarios. Developed by Rail Management Consultants GmbH, RailSys is a tool for digitalising railway infrastructure, scheduling timetables and simulating the scheduled timetables for different scenarios. In general, the software is divided into the following programs:

- Infrastructure
- Timetable
- Simulation and statistics

In this project, only Infrastructure and Timetable are applied to scheduling the timetables for the S-train scenarios. The simulation program is not used in this project.

With the infrastructure function the S-train network and its tracks, stations, speed limits and signal configurations are digitalised in a basis model. The purpose with this digitalisation is to formulate a model which looks like the real network with the same parameters. The function consists of the following tools:

- **Route:** Definition of single-track links and their parameters
- **Signalling:** Definition of the signals and signalling systems which are applied to the model
- **Electrification:** Definition of traction current for the specified railways
- **Level crossings:** Definition of level crossings on relevant lines
- **Stations:** Definition of stations on relevant lines
- **Lines:** Definition of an entire line, e.g. the existing TIB-lines and the Express Tunnel

In this project, the basic model is changed with the tools Route, Signalling, Stations and Lines.

With the Route-platform a specific link between two nodes can be defined with its length, speed limit, radius and cant. When two or more links are connected to a node a diamond crossing or turnouts can be defined.

Signalling is used to define signals, speed boards and balises and to model the block sections. Furthermore, no trackside signals should be located in order to define block sections with CBTC but it is still necessary to define virtual block sections from a virtual signal to another. Afterwards, the moving block configuration is applied to the block sections in order to permit more trains in the same block section at the same time.

The Station-platform is applied to define the new stations on the existing or new infrastructure. A station in RailSys is defined as stop boards, station boundaries and train routes. The train routes inside the station are defined from one station boundary to another and these parameters are then attached to the specific location of the new station.
The other program is “Timetable”. This function is linked to the infrastructure and all calculations regarding the technical running times are conducted on the basis of the defined parameters in the infrastructure. It means that the timetable-window can calculate a timetable for a train for 120 km/h on a specified line only if the track is defined with this speed limit.

The timetable-window in RailSys include three smaller windows: Train patterns and timetables, infrastructure and a graphical timetable. It is also possible to include a speed profile in order to visualise if the train utilise the speed limit on the line. The train patterns can be divided into S-train lines, i.e. line A, line B etc., as well as in northbound or southbound direction. The infrastructure illustrates the line on which the train runs and the stations it stops at. Furthermore, it is also possible to adjust the station routes in order to specify another entry from the line to another platform.

The graphical timetable illustrates the train’s timetable in a coordinate system with the specified line from the infrastructure window as the horizontal axis represents the distance and the vertical axis represents the time. The time range can also be adjusted in order to include more or fewer trains in the window. The timetable itself can also be adjusted by simply moving the graphical occupation up or down to change its time intervals. An example from the project is illustrated in Figure 30.

![Timetable Window](image)

Figure 30: Example of the timetable-window in RailSys with S-trains in moving block.

In the timetable-window it is possible to change the dwell time at the stations as well as the running time supplement. The technical running time is calculated by RailSys and if the running time between two stations is below the technical running time, RailSys will point out that there is a running time error for the specific train.

Furthermore, the timetable-program also includes different types of rolling stock which are attached to the specific timetable. It means that if the rolling stock type is changed and the timetable remain unchanged, it will be necessary to adjust the timetable afterwards – especially if the rolling stock accelerates slower than S-trains. If the present rolling stock is
changed to another type of rolling stock with better performances or if the infrastructure is upgraded to a higher speed limit, the timetable will be unchanged and the timetable-window uses the upgrade for running time supplement. Therefore, the user is always responsible for keeping the timetable as close to the best performance as possible.

4.4.1 Basic model – timetable S20 and basic infrastructure
The basic model consists of the basic S-train infrastructure as illustrated in Appendix 1 with the current lines and the basic timetable for S20. However, the new upcoming stations Vinge and Favrholm are also included in this model, but no trains stop there since the basic timetable is based on S20. Furthermore, the A line has its terminus at Hundige Station and does not continue to Solrød Strand every 20 minutes even though this is the case for the public timetable. An estimation of the running time to Solrød Strand is based on S20.

Furthermore, the signalling system CBTC is applied to all lines including the moving block configuration. Tracks in train depots like Copenhagen Central Station or Høje Taastrup are omitted.

4.4.2 Scenario models – scenario timetables and scenario infrastructure
Two scenario models in total are produced in RailSys:
- Scenario 1: Express Tunnel with stations at Forum and Vibenshus Runddel
- Scenario 2: Express Tunnel with an additional station at Rigshospitalet

Both Scenario 1 and Scenario 2 inherit the basic timetable and the basic infrastructure which are edited with new timetables and the Express Tunnel. The names “Scenario 1” and “Scenario 2” are kept for the remaining analyses in LTM.

The basic model is changed to the Scenario 1 model in which the infrastructure is changed since the Express Tunnel is digitalised into the network. In Scenario 1 the tunnel only includes the stations Forum and Vibenshus Runddel whereas Scenario 2 inherits the infrastructure from Scenario 1 but adds a station at Rigshospitalet. Furthermore, the links are also extended as a consequence from a longer tunnel.

The timetable for the S-trains is also changed and adapted to the new infrastructure with new lines and changes on the existing lines.

4.5 CBTC
One of the main assumptions in this project is the roll-out of CBTC – *Communication Based Train Control* – on all S-train lines. This system is divided into three main parts:
- The trackside equipment consisting of the interlocking, traffic management, train detection and balises for positioning
- Onboard equipment
- Communication system

Trains on CBTC-lines continuously send their current speed, direction and location over radio connection and the traffic control centre calculates the speed and the distance the train is permitted to run. The onboard unit controls the train’s speed and applies the
brakes and the speed and location are continuously determined. Consequently, CBTC-lines do not need trackside signals with normal light aspects (Fanea, 2019).

One of main parts of the technology is the concept moving block. On conventional railway lines with conventional signalling technology the capacity on the railway line depends on the number of fixed block lengths along the line. When the signalling systems has the moving block-concept included, the fixed blocks are removed and the headway to the train ahead is limited to the braking curve which depends on the distance and other circumstances. It means that the block no longer is fixed but “moves” with the train. Figure 31 below illustrates the concept behind CBTC.

![Figure 31: Difference between moving block and fixed block configurations (Fanea, 2019).](image)

With the fixed block configuration, a train occupies a specific fixed block length at a time. With CBTC, the headway between the trains is decreased to a brake distance to the train ahead (Fanea, 2019).

The capacity on the CBTC-lines is therefore not limited to a specific number of block sections as it is at the lines with the older system HKT. Here, the headway distance $S_h$ depends on the braking distance $S_b$, the length of the train ahead $L_1$, a safety distance $S_s$, a distance for receiving the movement authority $S_{MA}$ and the reaction distance to react on the movement authority $S_{React}$ with the following relation:

$$S_h \geq S_b + L_1 + S_s + S_{MA} + S_{React}$$

The “equal to or greater than” sign illustrates that the headway distance should be kept as a minimum value. Compared to a similar formula for calculating the headway distance for conventional signalling systems, this formula does not include the distances of the block sections since these are omitted in moving block systems (Landex, Rail Traffic Engineering - Spring 2014, 2014). Since the physical block sections are omitted, the headway time between the S-trains will be 90 seconds compared to 120 seconds with HKT.
(Banedanmark, u.d.). A graphical timetable for S-trains in a moving block configuration can be observed in Figure 30. It can be observed that the headway can be minimised to a low value since the block moves with the train. It is also observed that heterogeneous operation with fast trains and stopping trains has a limitation on the number of trains on the line.

5 Method: S-train scenarios in RailSys

This chapter describes the approach in implementing the Express Tunnel and scheduling the changed timetables for the S-train lines in RailSys.

5.1 Introduction and premises

This project is primarily about investigating the two alternatives of the Express Tunnel, how the public network will benefit and how the travel pattern will be changed by its implementation. In this case it is determined that if the focus should be on the Express Tunnel only, the current structure in the S-train network should be kept instead of changing the concepts on other lines, and it means that the current structure of skip-stop-service on the radial lines should be kept. Otherwise, the analysis would be broader since it would include a new concept and an analysis of the other lines as well.

Today, the radial lines except Dybbølsbro-Hundige and Hellerup-Holte according to Table 3 have a low capacity consumption since no more than 30 trains per hour in direction are operated via the central part Dybbølsbro-Svanemøllen. As illustrated in Table 3, the Boulevard Tunnel has still unused capacity during peak hours since the suggested consumption limit is 85% compared to 70% in daytime. But even though that more trainsets should operate through the existing central part, the travel time from one of the radials to another remain unchanged and it will still not be possible to obtain shorter travel times to and from the metro stations.

In order to obtain the shortest possible travel times from one radial line, to another e.g. Valby-Glostrup-Høje Taastrup to Svanemøllen-Farum, it is decided that the lines, that skip stops at the radial lines should be operated via the Express Tunnel in order to obtain the shorter travel times from the radials to new interchange opportunities to the metro network. The stopping trains are operated via Nørreport. With this concept the main focus will be kept on analysing the Express Tunnel and not a completely changed S-train network with other headways and service than today.

More trains on the branches Valby-Høje Taastrup as well as Valby-Frederikssund will be possible since the current capacity consumption from skip-stop-service on these lines does not exceed UIC max. This is also the current state for Svanemøllen-Farum and Hellerup-Klampenborg. However, Dybbølsbro-Hundige and Hellerup-Holte have today a capacity
consumption which exceeds UIC max in daytime which means that it is not recommended to operate more trains towards Hundige/Køge and Holte/Hillerød than today.

In general, the desired concept for the S-train scenarios should include the following characteristics:

- All radial lines from the hub stations towards the final station of the radial line should have a stopping line, which stops at all stations every 10 minutes, and a fast line, which skips stations with a low number of daily passengers, every 10 minutes as a minimum
- No pairs of stopping and fast lines at a radial line should continue along another radial line in the same combination. In this case, it is possible to obtain direct trains from one radial line to more radial lines at the same time
- Line F is the only line in the network which is not directly affected by the Express Tunnel. It means that this line will remain unchanged with the same headway and the same timetable
- Fast lines from the radial lines, which will be changed to the Express Tunnel, will be timetabled first. Afterwards, the stopping trains will be adapted to these lines
- The timetable should include minimum changing (2 min as the desired changing time) times between a stopping train and fast train on a radial line at a station where the lines towards Copenhagen Central Station and towards Forum diverge
- The ideal minimum headway time between the lines is supposed to be 2 min. With this headway between e.g. a pair of a stopping train and a fast train, the changing time can be short and delays in the timetable for one line to the following line can minimised by the short headways in CBTC

The fast line from Høje Taastrup to Valby is today line Bx. This line has its name from its status by supplementing line B during rush hour in the morning and in the afternoon hours on weekdays. In the new timetable it is decided to keep this line, but with 10 min headway during the day rather than 20 min during rush hour only. Since the line is a completely new line and not a supplementary line, the name of the line is changed to K.

In the basic model in RailSys with S20 the dwell times are defined as 16, 21, 26, 31 or 36 seconds. It is decided to use the same dwell times for the trains in Scenario 1 and Scenario 2 which means that the expected number of passengers on the stations are rounded up to the nearest dwell time in the mentioned interval. For Vinge Station, at which the dwell time according to the example in chapter 4.3 should be 15 seconds, the dwell time in RailSys will then be 16 seconds.
5.2 Infrastructure changes
Since this project does not concern the technical construction of the Express Tunnel but only an analysis of the alignment and stations, the length of the tunnel including connecting lines to and from the existing S-train lines at Ny Ellebjerg, Valby, Emdrup and Hellerup is measured on the basis of the drawing in GIS as illustrated in Figure 32 for Scenario 1 and in Figure 33 for Scenario 2.
According to the proposed alignment by Ekspresgruppen, the Express Tunnel should start at Emdrup and Hellerup and end at Valby and Ny Ellebjerg. By investigating the conditions around Ny Ellebjerg Station, the existing railway line from Dybbølsbro to Hundige and Køge and the new Copenhagen-Ringsted line as well as the freight line from Vigerslev to Copenhagen Airport intersect at Ny Ellebjerg and the platforms for the line towards Køge is above the other railway lines. It means that the line from Sjælør to Ny Ellebjerg is located on a ramp and it is therefore assumed to be challenging to locate the junction between these stations. In the meantime between the stations Sjælør and Sydhavn, the space between the S-train tracks and the tracks for the regional and intercity trains via Ny Ellebjerg is considered to be a more suitable location for the junction – see Figure 34. It means that Sjælør is used as the junction station.

Figure 34: Overview of the line from Sjælør to Ny Ellebjerg. The red circle indicates the approximate location for the junction.

The schematic layout plan for the tunnel in Scenario 1 illustrates that two underground interchange chambers have to be constructed in order to connect the two branch lines in the southern part and in the northern part of the tunnel. Since the southern interchange chamber is located far from Forum Station, the interchange chamber here is modelled as a station in RailSys with the name Carlsberg Nord, since it can be confirmed that it will be located in the northern part of the urban area Carlsberg Byen. This is, however, not a public station and no trains will stop there for boarding and alighting passengers. The northern interchange chamber is located close to Vibenshus Runddel Station which means that this will be modelled as such in RailSys.

The junction located at Hellerup is also located far from the station. In this case, the junction station, at which the branch from Hellerup to Vibenshus Runddel diverge, is like
Carlsberg Nord modelled as its own station called *Hellerup Syd* because of its location in the southern part of Hellerup. Hellerup Syd will have the same criteria as Carlsberg Nord. Since all stations in advance are defined by a station abbreviation, an abbreviation will also be assigned to the new stations:

- **Forum:** For
- **Vibenshus Runddel:** Vhr
- **Rigshospitalet:** Rih
- **Carlsberg Nord:** Cbn
- **Hellerup Syd:** Hls

The kilometrage in the Express Tunnel is defined from the turnout located at Sjælør Station in km 3.4 which changes to km 0.0 for the Express Tunnel. The reason for this is the length of the line Carlsberg Nord-Sjælør which is the longest connecting line from an existing S-train line to the Express Tunnel. From GIS it is measured that the different parts of the Express Tunnel have the following lengths as illustrated in Table 7:

<table>
<thead>
<tr>
<th>Parts of the Express Tunnel</th>
<th>Length [m] (Scenario 1/Scenario 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sjælør-Carlsberg Nord</td>
<td>1,842</td>
</tr>
<tr>
<td>Valby-Carlsberg Nord</td>
<td>806</td>
</tr>
<tr>
<td>Carlsberg Nord-Vibenshus Runddel</td>
<td>4,885/5,085</td>
</tr>
<tr>
<td>Vibenshus Runddel-Emdrup</td>
<td>1,727</td>
</tr>
</tbody>
</table>

*Table 7: Lengths in the Express Tunnel.*

It is illustrated in Table 7 that the length of the central part of the tunnel from Carlsberg Nord to Vibenshus Runddel differs from Scenario 1 to Scenario 2. The difference is caused by the changed alignment in Scenario 2 when the station at Rigshospitalet is added.

The Express Tunnel including the branches to and from the existing lines are modelled in RailSys for a maximum speed by 120 km/h since this is the maximum speed for the S-trains. However, when the branch lines diverge from the existing lines at the four junction stations the diverging track in the turnouts are modelled for a speed by 60 km/h to assure that the trainsets in the diverging track in the turnouts will have a lower speed than in the straight track.

The method behind modelling the tunnel infrastructure in RailSys follows the methodology as mentioned in chapter 4.4. The digitalisation is started at km 0.0 at Sjælør Station, and since the junction to the branch to Carlsberg Nord is located here, the station boundary at the existing station in RailSys is moved to a location after the new turnouts. This method is also applied to the junction at Valby Station. In Figure 35 this procedure is illustrated.

Similar models are used for the junctions at Emdrup and Hellerup Syd.
As Figure 35 illustrates the junction at Sjælør is modelled as a simple track layout with only two turnouts and no crossovers before and after the junction. The primary reason for this simple layout is because that only the running times in the Express Tunnel are calculated. If a simulation model in RailSys should be a part of the project’s scope more turnouts and crossovers would be have been implemented in the model in order to define alternative tracks in case of delays.

Figure 36 below illustrates the finished part of the Express Tunnel.
In Figure 36 the finished central part of the tunnel for Scenario 2 is illustrated. Vibenshus Runddel is a station for boarding and alighting passengers and an interchange chamber for the northern branches. Forum and Rigshospitalet are only stops for boarding and alighting passengers which is why these only are modelled as stop boards and station boundaries. The tracks are in the project assumed to be unidirectional which means that one track is specified for one direction only and the stations Forum and Rigshospitalet only include one train route in the specific direction. However, links in RailSys are defined as bidirectional which means that a link can contain a speed limit for both forward and backward directions.

At the station Vibenshus Runddel in Figure 36, a red signal is located next to the stop board. This indicates the endpoint for a block section and has to be located in the new infrastructure in order to schedule a train to run from one line to another. In this case it illustrates the endpoint for a route from a line to another, whereas the station boundaries define the routes inside a station only. Within the block section, it is defined that it has to be configured with moving block. Otherwise, only one train would occupy the block section at a time.

5.3 Timetable scenarios

The purpose with the project is as mentioned to analyse two timetable and network scenarios compared to the basic network in S20. In general, it means that the report refers to three different scenarios in the project.

The three different scenarios are all based on weekdays Monday to Friday. It means that it does not concern a changed timetable for weekends and holidays. However, the headway between trains on the different lines might be lower on these days because of fewer passengers than on weekdays.

As mentioned, Vinge and Favrhholm were included in the basic network in RailSys, but no trains were scheduled to stop at these stations. It means that stops also have to been applied for the trains in new scenarios.

The three timetable scenarios are the following:

Scenario 0/Basic scenario: The basic scenario and network map is illustrated in Figure 2. This scenario is assumed to the scenario in which the S-train network is not extended with the Express Tunnel. Furthermore, no trains stop at Vinge or Favrhholm since Vinge will be opened in 2020 and Favrhholm in 2022.

Scenario 1: The S-train network is extended with the new Express Tunnel with the stations Forum and Vibenshus Runddel. These stations are not new since they are served by the metro systems. However, they are not served by S-trains yet. The network map is illustrated in Figure 37.
Figure 37: Network map for Scenario 1. Interchange opportunities are also illustrated.

Compared to the basic network map in S20 in Figure 2, all lines are changed. The changes are listed in Table 8.
Line | Destinations | Headway
--- | --- | ---
A | Stopping train Farum-Hundige-Solrød Strand<br>Replaces line B Svanemøllen-Farum | Every 10 minutes, only every 20 minutes<br>Hundige-Solrød Strand
B | Stopping train Holte-Høje Taastrup<br>Replaces line E Hellerup-Holte | Every 10 minutes
C | Stopping train Klampenborg-Ballerup<br>Replaced by line H Ballerup-Frederikssund | Every 10 minutes
E | Fast train Hillerød-Forum-Køge<br>Changed to Express Tunnel and replaces line A Hellerup-Hillerød | Every 10 minutes
F | Hellerup-Ny Ellebjerg | Every 5/10 minutes
H | Fast train Frederikssund-Buddinge-Farum<br>Changed to Express Tunnel and replaces line Bx Emdrup-Farum | Every 10 minutes<br>Frederikssund-Buddinge, every 20 minutes to Farum
K | Fast train Klampenborg-Høje Taastrup<br>Replaces line Bx Høje Taastrup-Valby | Every 10 minutes
L | Hellerup-Åmarken | Every 10 minutes

Table 8: Description of lines in Scenario 1. The lines are reused in Scenario 2.

The digitalised infrastructure in RailSys is now applied to the timetable-platform in RailSys. It means that when a new train is inserted on the network, the running time between two stations, or at least a point the train can stop at, is calculated as the minimum technical running time.

The first step in changing the basic timetable to the Scenario 1 timetable is to keep the existing timetable for line F, since this line should not be affected in the new network.

Afterwards, the lines through the Express Tunnel are scheduled. The first rescheduled line is line E which replaces line A Hellerup (Hl)-Holte (Hot)-Hillerød (Hi). Since the running times and a timetable already exist for line A, the new line E inherits these running times.
and the service pattern by not stopping at the stations Bernstorffsvej, Gentofte and Jægersborg as well as Sorgenfri and Virum. This service is illustrated in Figure 38.

![Graphical timetable for lines B (green) and E (purple) between Hellerup and Holte. The window is extended to Allerød Station (Li).](image)

Figure 38: Graphical timetable for lines B (green) and E (purple) between Hellerup and Holte. The window is extended to Allerød Station (Li).

The new station Favrholm is a new stop for line E. It is expected that 4,600 daily passengers board and alight the train at Favrholm\(^7\) in 2032 (Danish Transport, Construction and Housing Agency, 2017). With the methods as listed in chapter 4.3 and 5.1, the dwell time will be 21 seconds. The graphical timetable for the remaining line to Hillerød is illustrated in Appendix 4.

The E line runs through the Express Tunnel to Sjælør and continues towards Køge with the same station pattern as today in S20. On this branch, line A and E is the same combination of lines as in S20 which means that only the arrival and departure times for these lines on this branch are changed so it fits to other lines. The graphical timetable for this service is illustrated in Figure 39.

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\(^7\) In the report “Trafikplan for den statslige jernbane 2017-2032”, the station is called Hillerød Syd.
Figure 39: Graphical timetable for the lines A (blue) and E (purple) between Hundige and Dybbølsbro. Between Åmarken and Dybbølsbro, line L (grey) is also illustrated.

The following line is line K. Due to the high number of passengers from especially Lyngby Station, it could be useful to schedule this line towards Lyngby. However, due to the skip-stop-service pattern between Hellerup (Hl) and Hillerød and the high capacity consumption, line K has its northern terminus at Klampenborg (Kl) to reverse. Since the concept behind skip-stop-service on all radial lines is kept, this line skips the stations Ordrup and Charlottenlund. A graphical timetable of this service is illustrated in Figure 40 below.

Figure 40: Graphical timetable of line C (orange) and K (pink) between Hellerup and Klampenborg.
Since the lines E and K continue toward the Express Tunnel between Hellerup and Hellerup Syd, they have to share the line Hellerup-Hellerup Syd with line F. Hence, in order to satisfy the desired headway time between the different lines, line E and line K should have a minimum headway between them by 4 minutes and 2 minutes between line F and line E as well as K respectively. From Valby (Val), line K replaces line Bx and keeps the same skip-stop pattern by skipping the stations Hvidovre, Rødovre and Brøndbyøster. Then it continues with stopping on all remaining stations to Høje Taastrup (Htå). The graphical timetable for this operation with line B is illustrated in Figure 41 below. On this figure, “Htå V” refers to the four depot tracks (V for “vendespor”) in the western end of the station – this is modelled as its own station in RailSys.

The last new line is H. This is the third fast line and operates today from Frederikssund to Østerport every 20 minutes. From Ballerup to Frederikssund this line runs in combination with line C without stopping at Kildedal Station. Both lines run in daytime on weekdays with a headway by 20 minutes, but since the lines are different and have a slightly different service from Ballerup to Frederikssund this line does not have an exact 10 min headway yet. It is therefore desired to run line H towards Frederikssund every 10 minutes and shorten line C to Ballerup.

Between Ballerup (Ba) and Valby (Val) line H remains a fast line every 10 min – instead of every 20 min in S20 - and skips the stations Skovlunde, Islev, Jyllingevej, Peter Bangs Vej and Langgade as in the timetable today. However, Husum has more passengers among the stations that line H skips today and it is decided to include a stop for line H at Husum.
In 2032 it is expected that Husum has 5,800 daily passengers (Danish Transport, Construction and Housing Agency, 2017). It is decided to let line H stop at all station from Ballerup to Frederikssund even though that Kiledal Station only has a very limited number of daily passengers compared to other stations. However, the timetable for a specific line would be more complicated and not periodic, if line H should stop at Kiledal every 20 minutes only. The graphical timetable for lines C and H is illustrated in Figure 42 below. The station “Ba V” refers to the depot tracks at Ballerup Station – this is modelled as a station in RailSys.

Figure 42: Graphical timetable for line C (orange) and H (red) between Ballerup and Valby. The window is extended to Kiledal (Kid) to the left.

The line between Emdrup and Farum is the northern radial line for line H which replaces line Bx. It is desired to implement a fast line on this line as well as on the other radial lines. However, line Bx is a stopping line in S20, and in order to construct a timetable for skip-stop-service, the timetable S18 from 2018, in which line Bx was a fast line with skipping Emdrup, Dyssegård, Kildebakke and Skovbrynet, it is decided to adopt this timetable and service for line H. Contrary to S18, line H has a stop at Emdrup because the lines A and H diverge at this station and the short changing time between these lines can be obtained here.
In the meantime, the single-track line from Fiskebæk to Farum on the line Svanemøllen-Emdrup-Farum is a bottleneck and an obstacle in operating two lines every 10 minutes to Farum. The primary reason for this statement is a conflict between two trains on the line since these will conflict on the single-track part. This is illustrated in Figure 44 below.

![Figure 43: Graphical timetable for line A (blue) and H (red) between Svanemøllen and Farum.](image1)

![Figure 44: Illustration of the string line timetable Værløse-Farum.](image2)
Between Fiskebæk and Farum, the line is single-tracked which means that an additional line H every 20 minutes to and from Farum will conflict at the single-track part. It is also observed in Figure 43 that there is a high proportion of the capacity between especially Buddinge and Farum which is unused. However, the depot track (22) at Buddinge Station makes it possible to reverse a train without occupying the platform tracks – see the schematic drawing in Appendix 1. In this case, line H is operated on Frederikssund-Buddinge every 10 minutes and to Farum every 20 minutes. Since the three lines E, H and K are operating through the Express Tunnel every 10 minutes, the number of trains through the tunnel is 18 per hour in each direction. The graphical timetable for the tunnel is illustrated in Figure 45.

![Figure 45: Graphical timetable for the lines E (purple), H (red) and K (pink) in the Express Tunnel.](image)

The dwell times at the new stations Forum and Vibenshus Runddel are in this case estimated since the number of daily passengers at these stations have to be calculated by the National Transport Model. According to the basic timetable in RailSys the dwell times 31 and 36 seconds are applied to stations with a high number of daily passengers – especially at interchange stations. In this case, 31 seconds as dwell time is applied to Forum and Vibenshus Runddel but in future operations or timetables, the dwell time should be raised if the stations are expected to service a higher passenger volume.

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8 In RailSys, the depot track is modelled as its own station, “BudVen”. This is also the case for other stations.
The lines A, B and C are then adapted to the lines in the Express Tunnel. However, the following changes apply to the three lines:

- The same stops as in S20 remain for line A between Solrød Strand-Hundige and Svanemøllen. From Svanemøllen line A replaces line B towards Farum with the same stops and running times as line B in S20
- Line B has the same stops between Høje Taastrup and Svanemøllen with the same running times as in S20. From Svanemøllen line B replaces line E towards Holte with the same stops and running times as line E in S20
- Line C is almost unchanged. Line C is, however, removed from Ballerup-Frederikssund, since it is replaced by line H on this line
- Line F remains unchanged

In the meantime, line Bx, E and H from S20 are removed from the existing tunnel via Nørreport Station which means that 12 trains on the central part of the network during peak hours (9 trains outside peak hour) are removed. In order to operate more trains through Nørreport Station, a new line, line L, is introduced to the S-train network. This line should at least stop at the stations Dybbølsbro-Svanemøllen to service the central part of the network, but it is difficult to find termini for this line because the stations Valby and Hellerup are now highly utilised stations since 24 trains per hour in each direction at Valby and 36 for Hellerup (including line F). It is assumed that the high capacity consumption between Hellerup and Holte is a bottleneck for further lines according to UIC’s recommendations for maximum capacity consumption and the number of passengers on the line to Klampenborg is lower than on the line to Holte and Hillerød (Danish Transport, Construction and Housing Agency, 2017). Furthermore, no more trains on the line towards Farum is a possible option, since the line Værløse-Farum is a bottleneck and the depot track at Buddinge is occupied by line H.

Meanwhile, the capacity consumption on the line Dybbølsbro-Ny Ellebjerg is the same since the number of trains Sjælør-Ny Ellebjerg-Hundige remains unchanged. The following station after Ny Ellebjerg in direction Hundige and Køge is Åmarken, which has a depot track (0) in the western end of the station. It is therefore assumed that this line can reverse in this track, but since it is not electrified for the electric S-trains or equipped with a turnout from track 2 to track 0, these elements have to be constructed.

In the northern end, Hellerup Station has a variety of depot tracks. Today, the depot tracks 61 and 62 are used by line F, since this line does not have to reverse at platform track and occupy it for other trains at the same time. But the depot tracks 15 and 16 are not used in daily operation in the S20-timetable⁹. It means that these are vacant for an additional line and it is decided to let line L use these tracks for reversing.

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⁹ According to the basic model in RailSys.
**Scenario 2:** This scenario inherits the changed network and timetables from Scenario 1, but the station at Rigshospitalet is now added to the Express Tunnel and the tunnel itself gets a longer length, since it now has to be located closer to Rigshospitalet. The lines and headways as well as the different routes at Hellerup Station remain unchanged.

![Network Map for Scenario 2](image)

**Figure 46:** Network map for Scenario 2. Interchange opportunities are also illustrated.

The dwell time 31 seconds is also applied to the station at Rigshospitalet. The stop at the additional station results in an extended running time through the Express Tunnel since the trains on line E, H and K have to brake, stop and accelerate again at the new station. Due to the additional stop, the timetable for the radial lines will be changed since the arrival and departure times are changed. Some lines will depart earlier from the termini and the changed timetables also influence the trains on the lines via Nørreport since these
have to be adapted to the changed timetables for the lines via the Express Tunnel. A new graphical timetable for the Express lines is illustrated in Figure 47.

![Figure 47: Graphical timetable for lines E (purple), H (red) and K (pink) for the Express Tunnel in Scenario 2. A new stop at Rigshospitalet (Rih) is added.](image)

Since a third station in the Express Tunnel is added the capacity consumption will be increased. However, as the next paragraph mentions the new consumption will not be close to UIC max.

The total number of S-trains per hour at Hellerup Station is then 42 for Scenario 1 and Scenario 2, which is assumed to be a high number for the station with many conflicting routes from and towards different lines. It also means that simultaneous arrival and departure routes at the station from different lines have to be handled in a way that these routes do not conflict. An example for a conflict is between line C towards Klampenborg and line E towards Hillerød which arrives at Hellerup at the same time. In S20, line C is scheduled to arrive in track 3 and line E in track 4. This would be a conflict with crossing train routes from Hellerup Syd and Svanemøllen and in direction north, but the conflict is resolved by assigning track 5, which normally is used by line F only, to line E.

An overview of the different routes for lines stopping at Hellerup is illustrated in Figure 48.
As illustrated it is necessary to define specific routes for the different S-train lines in Hellerup in order to avoid conflicts with diverging, converging and intersecting train routes. However, since the utilisation of the platform tracks is high the station might be a bottleneck and incidents happening at Hellerup will cause delays on the different lines. Another example of a station many diverging and converging trains routes is Valby Station since two radial lines with 24 trains per hour per direction in total will diverge and converge at this station.

5.4 Results

The main results from the timetabling procedure in RailSys are the finished timetables. In RailSys, the running time between stations is illustrated in seconds, and the arrival and departure times are illustrated in hours, minutes and seconds in the following format: HH:MM:SS. However, a timetable for the public would normally be presented by indicating the approximate departure time from the stations as well as the arrival time at the terminus. In order to do so, the following method apply to presenting a public timetable:

- Departure time at stations except terminus is rounded down
- Arrival time at a terminus is rounded up

Hence, the public timetables have also been conducted for the lines in the new S-train network. These are illustrated in Appendix 2 for Scenario 1 and in Appendix 3 for Scenario 2.

Regarding the capacity consumption in the new network, it can be stated that the bottleneck between Dybbølsbro and Svanemøllen has fewer trains than before the implementation of the Express Tunnel. However, all branch lines except Hellerup-Holte
get more departures and new lines which raises the capacity consumption. Figure 49 below illustrates if the lines in the S-train network exceed the recommended maximum capacity consumption on a daily average. In this case, the recommended maximum capacity consumption is 70%. “Close to UIC max” is in this project defined as above 60%.

Figure 49: Illustration of capacity consumption in the S-train network in Scenario 1 and Scenario 2.

In Figure 49, it is also illustrated that the line Værløse-Farum exceeds UIC max. This special case refers to the bottleneck on the single-track line – it is not possible to operate more trains with the current pattern of lines.

With the suggested timetable and lines, the Express Tunnel leads to significant travel time reductions not only in the S-train network but also for other stations in the metro network. One example is from the southern and western branches to and from Nørreport Station, since a travel time reduction by 2 min can be obtained. However, a change to the metro at Forum Station is necessary. Further results are illustrated in Figure 50.
Figure 50: Travel time reductions from diverging stations in the S-train network to the Express Tunnel. Ny Ellebjerg is used instead of Sjælør since this is a hub for more transport modes. Red numbers in parentheses are in Scenario 2.

The travel time reductions are calculated with current travel times in S20 as well as timetables for buses and metro as reference\(^\text{10}\). Time for interchanges between S-train and metro in the new network is estimated to 3 minutes.

\(^{10}\) From Rejseplanen. A weekday and a time at 08.00 are selected as a reference.
Another major benefit from the Express Tunnel is the travel time reductions between the radial lines in the network. The figures, Figure 51 and Figure 52, below illustrate the reductions by comparison to the travel time today via Nørreport.

As illustrated, the travel time reduction varies depending on the direction. Hence, only 4 to 5 minutes can be saved from the Høje Taastrup-branch to the Farum-branch whereas the reduction will be higher in the opposite direction. This is because of the changing time between line K and line H in the Express Tunnel. However, the travel time reduction will
vary if the lines from one branch to another is changed. It means that the reductions are based on the timetables from Scenario 1 and Scenario 2 only.

Figure 52: Travel time reductions from Køgebugtbanen to the branches towards Farum, Hillerød and Klampenborg. Another additional reduction can be obtained to and from the metro station Frederiksberg.

As Figure 52 illustrates the reductions in travel time are significant between Køgebugtbanen (the Køge-branch) and the northern branches. Furthermore, it will also be faster to travel to Frederiksberg Station as well as the metro stations on Amager via Forum Station.

Another advantage for the branches towards Farum, Hillerød and Klampenborg is that a travel time reduction between these branch lines to the metro line Cityringen (M3) can be
obtained. The reason for this is that the travel time from these branches to Vibenshus Runddel is shorter than the travel time today to and from Østerport Station which is an interchange station to line M3 and from 2020 to M4. The travel time reductions are illustrated in Figure 53 below.

As observed, only the northern branch lines will benefit from the Express Tunnel. From the southern branch lines no reduction can be obtained.
6 Assignment model and calculation

This chapter introduces the National Transport Model and the structure in it since it is inspired by a so-called four-stage model. Since this project is based on a model in the public transport network, the theory behind the elements for this mode is introduced whereas the road traffic model, freight model and air transport model are not commented in detail.

6.1 Introduction to the National Transport Model and assignment models

The purpose with the National Transport Model is, in general, to provide a homogeneous basis for decision in order to spend the resources in the best possible way and especially to develop a coordinated transport model across different sectors, government agencies and companies (Nielsen & Pause, Kursus i Landstraflakmodellen, 2019). The entire country is modelled and divided into 907 zones and the concentration of zones is higher in Copenhagen and other cities than in the rural areas.

The modelling of trips in the network with different transport modes in LTM – public transport as well as car – is inspired by a four-stage model. The purpose of this model is to model demand for travel and supply for travel in a network, from where demand defines the number of passengers in the network, e.g. with a specific train or bus line, and supply defines the variables within the transport system. One example of variable could be the average travel time with an S-train line in the Express Tunnel.

The modelling of transport is a dynamic approach since an assignment model always will use more iterations to model the transport. However, the four-stage is a static approach since it follows four steps in a specific row. The upper levels set conditions for the lower levels and the lower levels induce changes in the input to the upper levels (Mabit, Transportation System Analysis - The four-stage model and trip generation, 2017). This procedure and the four steps are illustrated in Figure 54 to the right.

The first step is Trip generation. The role with this step is to determine the number of generated trips from each zone in the network and the number of trips attracted to each zone. It means that this step models all tours in the network, and since a trip always has an origin and a destination, the number of attracted trips is equal to the number of generated trips. However, this step does not distribute the trips in in the so-called OD-matrix, which includes the specific pair of origin to destination zone, since this is done in the following step. The generation of trips is based on different socio-economic variables about a specific zone such as type of job, income and age. However, also the accessibility in the zone is
also considered since a trip with public transport will not be generated or attracted if the public transport is not accessible.

The trips are distributed in specific OD-pairs in the second step Trip distribution. In order to distribute the generated and attracted trips, this step takes a general cost for a trip between the origin zone \( i \) to a destination zone \( j \). The generalised costs can then be expressed as \( c_{ij} \) for the cost of the pair \( i-j \) and can define a function of distance or a weighted sum of both travel costs and travel time. The model for the sum of trips \( T_{ij} \) can then be expressed with the following formula:

\[
T_{ij} = A_iB_jO_iD_jf(c_{ij}).
\]

The factor \( f(c_{ij}) \) refers to a function of the generalised costs. \( A_i \) and \( B_j \) are balancing factors to assure that the sum of generated trips in the OD-matrix always is equal to the demanded trips and in the opposite way for attracted trips (Mabit, Transportation System Analysis - Trip distribution, 2017).

When the trips are generated, attracted and distributed among the different zones, a transport mode has to be chosen. The choice between transport modes is a discrete choice since the choices for a transport mode excludes the other modes. In order to model the choice between modes, a utility function for choosing one specific transport mode is defined as

\[
U_i = V_i + \varepsilon_i = \alpha_i + \beta_{ix} + \varepsilon_i.
\]

In this formula for the utilisation of choosing transport mode \( i \), \( U_i \), \( V_i \) refers to the systematic part of the function and \( \varepsilon_i \) to an error term from the modelling of these functions. \( x \) are variables for the choice, e.g. socio-economic variables or variables for time and costs and \( \alpha_i \) and \( \beta_i \) refer to parameters for the specific mode. The utility functions have to be specified for one specific mode, since another mode will have another utility.

Finally, the probability of choosing a specific transport mode \( i \) among all modes \( j \) is given by the logit-model:

\[
P(i|\boldsymbol{x}_n) = \frac{\exp(V(x_{ni}))}{\sum_j \exp(V(x_{nj}))}.
\]

Here, \( n \) refers to the individuals in the model network.

The last stage Route assignment defines the specific route for the trip from an origin zone to a destination zone. The primary problem for this stage is to find the equilibrium flow pattern in the transport network, which is a trade-off between demand and the capacity available on a given link. The assignment model is therefore built up from three blocks:

- A speed-flow relationship that control the trade-off between the traffic load and travel time
- An assignment models that control the demand to the network
- An equilibrium that controls the system
The demand model in LTM is based on different assumptions for the different zones. It is assumed that the different zones have a specific population, a specific number of jobs and a defined infrastructure. Moreover, all 907 zones in LTM are attached to a specific municipality since data about extrapolation is based on a municipality level. The initial population and number of jobs are from 2010 and the population data is based on different socio-economic data including sex, age, income, labour market association, family status and number of children. The population is extrapolated for every five years from 2010 from where jobs are divided into different sectors and extrapolated with the national growth for the specified sector.

Furthermore, the demand model for public transport, walk, bike and car depends on the car ownership for the different households. The car ownership is modelled as if a household has 0, 1 and 2 or more cars but is not depending on the type.

Figure 55: Overview of the structure in LTM 2.0/2.1 (Rich, Modellering af efterspørgsel LTM 2.0/2.1, 2019).

When the demand in LTM is modelled, the internal traffic in Denmark on an average weekday is divided into six trip purposes which are divided into primary and secondary trips. The demand depends on the mode choice, destination and the number of trips. The modes are walk, bike, car, car passenger, public transport and plane, whereas the destination is based on the 907 zones in LTM. Furthermore, it is also possible to model cross-border traffic to Sweden and Germany, but since this project is limited to the capital region, this traffic is not investigated.

The demand and route choice have an influence on each other, since the demand affects the route choice and the route choice affects the demand. Therefore, the convergence
depends on a weighted average of the travel times before they are applied to calculating the demand (Rich, Modelling af efterspørgsel LTM 2.0/2.1, 2019). Since LTM only is inspired by the four-stage model there are some differences between this model and the four-stage model. First and foremost, the generation model does not model trips but so-called *tours* which only takes the directional information into account and not the symmetrical outbound and return trip like in an OD-matrix. The OD-matrix consists of all trips from outbound and return trips whereas the so-called GA-matrix (for generation-attraction) has an outbound trip connected to a return trip (Rich, Matrix estimation methods, 2017). The tours are modelled from the logit-model which is equal to the logit-model for mode choice as mentioned earlier. However, the logit model for generation models the probability for a specific number of tours. Afterwards, the GA-matrices are converted to OD-matrices in order to model the return trips as output.

LTM is not based on the gravity model as mentioned earlier since the distribution and the mode choice are combined as one stage. In this case, the choice of mode and destination is modelled with a so-called nested logit model in which different choices can be divided into subsets called nests. A nesting structure could be to divide the mode choice into car alone or public transport from where public transport again consists of sub-choices with different public transport modes such as bus or train. This is the case for LTM since the upper level consists of car ownership and the lower levels for transport related to transport related choices including trip frequency, destination choice and choice of mode. The demand model is then linked with the assignment model with stochastic user equilibrium in order to represent congestion effects and the fact that increased demand is counteracted by lowered accessibility due to congestion (Hansen & Rich, 2016). The congestion effects and the stochastic user equilibrium do, however, only apply to car assignment. For example, the travel time $t$ on a specific road depends on the link volume on the road which is expressed with the BPR-formula:

$$t = t_0(1 + \alpha(x/C)^\beta),$$

from which $t_0$ is the free-flow travel time, $x$ is the link volume, $C$ the link capacity and $\alpha$ and $\beta$ are parameters depending on the road type and area.

The public assignment model in LTM is entirely based on a schedule. It means that the exact timetable as rounded to a public timetable is the basis for the movements of the different public transport modes which are defined as trains, metro, buses and ferries. The mode “train” is also divided into different modes such as S-train, regional train$^{11}$, intercity train and metro. Local trains and light rail is the same mode whereas the modes ferries, buses and long-distance coaches also exist.

All the national lines divided on the different transport modes are included in the model and lines to Sweden and Germany and to other foreign countries are also modelled. Since the public network is based on the timetable, it is easy to model the flow on lines and

$^{11}$ This mode is also divided into regional trains operated by DSB and by Arriva.
between the modes in the network. However, it then assumes that all public transport modes are always on time and no delays can occur in the model. It also assumes that no congestion in the network occurs, which means that there is always enough space for every passenger in the rolling stock (Nielsen, LTM Usikkerhed, kvalitetssikring, muligheder og begrænsninger, 2019).

In general, there are three purposes for a trip with public transport: Commuting, Business and Other. These are also presented with a specific utility function which have an influence on the transportation mode. When a trip is generated for a purpose, there are five different time intervals to be considered. These are:

- **Vehicle time**
The time a passenger is in the specific transport mode from one stop to the destination or interchange stop. This is based on the timetable in the public transport model.

- **Waiting time**
The waiting time is defined as the time the passenger will wait at the specific transport mode at the stop.

- **Changing time**
The time it takes a passenger to change from a mode to another mode. This is based on the time specified on a public change (see chapter 6.3). When a passenger has to change to another transport, a monetary value as a penalty is assigned for the change (see chapter 7.3).

- **Access/egress time**
The time it takes the passenger to access and egress a stop from the origin to the destination. This is based on the time specified on connectors (see chapter 6.3).

- **Hidden waiting time**
The hidden waiting time in the public transport network is defined as additional waiting time for the transport mode. This depends on the headway between two trains or buses from the specific stop and the passengers will therefore adapt to this with waiting before accessing the specific stop.

The connection between the above-mentioned time intervals is illustrated in Figure 56.
As illustrated, the total travel time with public transport depends on several time intervals, and even though Figure 56 illustrates a change between two transport modes, some journeys might also exist without changing or with more changes. The choice of transport mode within the public transport network is determined in the assignment model without capacity restrictions which is the case for the car assignment model.

6.2 Scenarios and conditions

For implementing a new scenario in LTM based on changes in the public transport network, the application LTM Manager by Rapidis is used. This software is the user interface for LTM and builds up the structure for the different model scenarios. Before adding a new scenario to the database, it should be considered if the new scenario have to be based on a previous scenario with infrastructure and lines. Different scenarios are already defined in LTM Manager, where one newer scenario inherits the public transport network from the previous scenario. It also means that the columns in the database for a specific attribute will be inherited to the new scenario, if this scenario is based on the previous scenario. Figure 57 to the right illustrates how this hierarchical structure looks like in LTM Manager.

The new main scenarios in LTM Manager are based on adopted and opened projects as well as the timetables from Trafikplan 2032, which means that the new scenarios inherit the data such as railway links, lines and line variants from Trafikplan 2032. In the meantime, and due to the inheritance-procedure, Trafikplan 2032 has already inherited the data from Trafikplan 2027 and similar for the other scenarios.

The main scenario is built up from sub-scenarios. These sub-scenarios are:

- Public Rail Link Scenario
- Public Change Scenario
- Public Connector Scenario
- Public Route Scenario

Only the first three of the four listed sub-scenarios inherit Trafikplan 2032. The last one, Public Route Scenario, is unique for the new main scenarios, which means that it cannot inherit the previous scenario. For Scenario 1 and Scenario 2, the unique scenario number in LTM Manager is in this case 101 and 102 respectively, and both 101 and 102 inherit the column “Free Speed” from the previous Trafikplan 2032. Only the column “Active”
becomes a new column in the database for these scenarios, and the column indicates if the specific feature is activated or deactivated to be used in calculations with a binary number.

In order to build up the scenario models for the new S-train service, the following conditions apply to the models for the main scenarios 101 and 102:

- The basis for the scenario models is Trafikplan 2032. It includes all the mentioned projects and new lines from chapter 2.
- No regional trains stop at Glostrup. Even though a stop for regional trains at Glostrup in proposed as a condition for Ring Syd, the railway network Trafikplan 2032 in LTM does not consist stops at Glostrup Station for this train category.
- The timetable for the local railway trains is based on a 2015-timetable. As a consequence, no local trains stop at Favrholm. Favrholm (as well as Vinge) is included in Trafikplan 2032 and modelled with the name “Hillerød Syd”. This station has stopping S-trains with line E in Trafikplan 2032, and this service will be continued.
- The bus network in LTM is from 2015, which means that the new network, Nyt Bynet, from 2019 is not included in LTM and this is also not adapted to Cityringen or the new light rail on Ring 3. It also means that the bus service and the light rail run in parallel on Ring 3.
- The light rail line on Ring 3 has another alignment than modelled in LTM. Trafikplan 2032 in LTM includes an alignment along Lundtoftegårdsvej in Lyngby, but the alignment is later changed to run into the campus area at DTU along Akademivej and Nils Koppels Allé. The current alignment in Trafikplan 2032 is, however, kept.
- The timetable for metro and for Øresundstog is from 2010.
- No changes of other transport modes than S-trains with regards to Lines, Line variants, Schedules and Runs have been prepared. Even though that some conditions after the modelling of these modes and lines have been reformulated or new projects adopted, the model in LTM remain unchanged.

### 6.3 Public transport network and method

The main tool for editing the public transport network in LTM is the tool Traffic Analyst in the GIS-software. This tool has several functions, which are elaborated in this chapter. The railway infrastructure is modelled as Links. A link is defined as a piece of a railway line which means that a double-track line is also modelled as only one link and not a link for each track. The infrastructure for the Express Tunnel is then modelled with links, and even though that two alternatives are defined for this tunnel in this project, only one infrastructure is modelled since the service on the infrastructure is defined on the specified schedule. It also means that a speed limit on the infrastructure is not defined, since the timetable has to be specified in advance. In order to connect the new infrastructure to the existing lines, some of the existing links are split up and defined as two new unique links.
The stops in the public network are modelled as public route choice stops. Only three new stops are modelled in the changed scenario: Vibenshus Runddel, Rigshospitalet and Forum. At Vibenshus Runddel and Forum, stop nodes already exist since these are metro stations as well. However, in order to investigate the number of changing passengers between the public transport modes, the new S-train stations are modelled as new nodes. For calculations in Scenario 1, the new station nodes Vibenshus Runddel and Forum are active, whereas Rigshospitalet is deactivated. This is active for Scenario 2. The stations Carlsberg Nord and Hellerup Syd are not modelled in LTM since only stations, at which the trains stop at for boarding and alighting passengers, are included.

In the new nodes, the minimum changing time for internal changes to other lines or trains at the same node has to be specified. This is assumed to be 1 min since this time also applies to the corresponding metro nodes.

Afterwards, the interchange opportunities to other transport modes have to be specified. One of these is especially the interchange between the S-train and the metro at the stations Vibenshus Runddel and Forum. For this purpose, the model feature Public changes is applied. This tool models and determines the number of changing passengers from one mode to another, and the main quantity for determining the goodness of changing is the changing time. In order to determine this, the following methods are applied:

- **Vibenshus Runddel:** At this station, connection to the metro line M3 as well as the bus lines can be obtained. In order to determine the changing time, this station is compared to Flintholm Station, at which changes between S-trains and metro is available and the passengers have to use stairs or elevators twice in order to walk between the two platforms. The changing time for this station between these modes is 3 min. This is applied to Vibenshus Runddel for the metro and the bus stop.
- **Rigshospitalet:** In order to determine the changing time to the existing bus stops around Rigshospitalet, a specific method has been developed on the basis of a walking speed by 4 km/h. This might be a bit low but takes slower passengers into account. Example:
  - The distance between the new S-train station and the bus stop Blegdamsvej/Tagensvej is 123 m. The time for accessing the bus stop from the station is then:
    \[
    \frac{123 \text{ m}}{\frac{4 \text{ km/h}}{3.6 \text{ m/s}}} = 93 \text{ s}
    \]
    Finally, this time is rounded up to whole minutes which is 120 s = 2 min in this case.
- **Forum:** Four stop nodes have been identified for this station: Metro line M1 and M2 and the bus stops Forum St., H. C. Ørsted's Vej/Rosenør's Allé and Danas Plads. These bus stops are selected since a public change link between these stops and the metro already exist. It is therefore decided to use the same interchange relations as
the existing metro lines, and the changing time for these relations are also applied to the new S-train node. For the changing time to the metro, Flintholm is used as the reference.

A main assumption for the public changes is, that the existing connections to other modes have to be applied to this S-train stations.

Finally, the passengers in the public transport network should also have the opportunity to start and finish the journey at the new stations. For this purpose, the tools Centroids and Connectors are applied. A centroid is defined as the centre of the zones in LTM and these are as the points at which the traffic, i.e. the passengers in the public network, begins and ends. The connectors are the links from the centroids to the public transport nodes and these are specified with a length and a time. If a connector is defined from a specific node to a centroid, the passengers can start and end the journey at the specified zone from that station. Since a connector is defined with a time, the access and egress time for the trip is defined as this time.

For identifying the relevant zones and centroids, the existing metro nodes and bus stops are used as references. If a connector exists from a node to a centroid at the same location as the new S-train nodes, the same connector will also be modelled for the S-trains. In this case, the same specified travel time on the existing connectors are assigned to the new connectors.

An overview of new stations and connecting zone centroids and public changes is listed in Table 9 below. Figure 58 and Figure 59 illustrate the public network in LTM12.

<table>
<thead>
<tr>
<th>Station</th>
<th>Connectors to zones</th>
<th>Public changes to other stops</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vibenshus</td>
<td>Ydre Østerbro V – 7 min</td>
<td>Metro line M3 (Cityringen) – 3 min</td>
</tr>
<tr>
<td>Runddel</td>
<td>Ydre Nørrebro N – 10 min</td>
<td>Bus stop Vibenshus Runddel – 3 min</td>
</tr>
<tr>
<td></td>
<td>Rigshospitalet – 14.4 min</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Indre Østerbro N – 14.6 min</td>
<td></td>
</tr>
<tr>
<td>Rigshospitalet</td>
<td>Rigshospitalet – 3.1 min</td>
<td>Fredrik Bajers Plads – 5 min</td>
</tr>
<tr>
<td></td>
<td>Indre Nørrebro S – 8.6 min</td>
<td>Rigshospitalet – 4 min</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Blegdamsvej/Tagensvej – 2 min</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rigshospitalet Fjernbus – 5 min</td>
</tr>
<tr>
<td>Forum</td>
<td>Indre Nørrebro S – 13.2 min</td>
<td>Metro line M1 and M2 – 3 min</td>
</tr>
<tr>
<td></td>
<td>Ydre Nørrebro V – 16.6 min</td>
<td>Bus stops: H. C. Ørsteds Vej – 3 min</td>
</tr>
<tr>
<td></td>
<td>Frederiksberg Øst N – 10.8 min</td>
<td>Rosenør Allé – 4 min</td>
</tr>
<tr>
<td></td>
<td>Frederiksberg Øst Ø – 7.2 min</td>
<td>Danas Plads – 7 min</td>
</tr>
</tbody>
</table>

Table 9: Overview of connectors to zone centroids and public changes to other transport modes. The time in minutes on these features indicate the travel time between stop nodes or from a stop node to a centroid.

12 Please note that the railway network in Figure 59 also includes a metro line from Vanløse Station to Rødovre. This line is only implemented as an exercise and is not in operation in basis or in any of the two scenarios.
Figure 58 illustrates that the new station “Vibenshus Runddel St” node is connected to the metro station node “Vibenshus Runddel (MCR)” and the bus stop “Vibenshus Runddel” to the left via public changes illustrated as the pink lines. The blue lines are connectors and the black intersecting links are the Express Tunnel and the metro line Cityringen. Yellow lines are bus lines.

Figure 59: Map of the public transport network in Copenhagen after the implementation of the Express Tunnel. Yellow dots are bus stops – light rail and metro stops are modelled as railway stop nodes.
After the implementation of the Express Tunnel in LTM, the timetable from RailSys for the S-trains have to be implemented. This procedure is implemented with four features which also represent four steps: Line, Line variant, Schedule and Runs. These features are also in a hierarchy (see Figure 60) which means that a Line variant is based on a Line, a Schedule is based on a Line variant and a Run is based on a Schedule.

The first step is the Line. This feature defines a specific line from terminus to terminus on the physical railway infrastructure. One example for this is the new line H from Frederikssund to Farum via the Express Tunnel. One line is defined from Frederikssund to Farum and a second line is defined for the opposite direction.

The sub-feature to Line is Line variant. As mentioned, this is based on the feature Line but indicates if this line has specific variants. One variant could be that a specific train line has 10 min headway and run to the final terminus every 20 min and is limited to another station every 20 min. In this project, the line variant is especially important for line H since this line runs between Frederikssund and Buddinge every 10 min but is extended to Farum every 20 min. It means that two line variants in the direction Frederikssund-Farum are defined and two in the opposite direction. In total, four Line variants are implemented for two Lines.

The next feature to be defined is the Schedule. This feature is defined as the specific timetable for the train or, in details, for the specific line variant. It means that each Line variant has to be assigned one schedule and one Line will therefore consist of two Schedules.

To specify the schedule, it is necessary to carry out a timetable or at least calculate running times between the stops for the train or other public transport mode in advance. Since this is carried out in RailSys, the public timetables from Appendix 2 and 3 are applied to this feature. The schedule does not manage the specific arrival and departure times directly since it only uses the running times between the stops, i.e. the train will always depart from the first station on the line variant in the time 0. Furthermore, it should also be indicated if the train has to stop at one specific station and if passengers can embark and/or disembark the train at the station. For the previous example with line H from Frederikssund to Farum, this train will depart from Frederikssund at the time 0 and arrive (and leave) the next station Vinge at the time 3 according to the public timetable. Even though that this line will skip several stations such as Skovlunde Station, an arrival and departure time have to be specified. This is done on the basis of the theoretical timetable in
RailSys. Copenhagen Central Station is the only station at which the arrival time and departure time differ – the dwell time is her modelled as 1 min.

An example of a specification of a Schedule is illustrated below in Figure 61.

![Figure 61: Specification of a Schedule and Runs in Traffic Analyst - in this case for line H Frederikssund-Farum in Scenario 1. No passengers can embark or disembark the train at, for instance, Skovlunde and Rigshospitalet.](image)

The last element is Runs. Since this feature is based on Schedule, the Run indicates the specific train with the specified schedule on the specific line variant. A Run is defined with a departure time from the first station on the line variant and the specified number of Runs is assigned to the specified Schedule.

In order to define the service and the number of Runs in Scenario 1 and Scenario 2 for the different lines, a reference is selected to be the weekdays in S20. In this timetable, all lines run every 20 minutes in early morning hours and in evenings after 8:00-8:30 PM. The lines E and H are, however, taken out of service in the evening on weekdays. In this project, all lines will run every 20 minutes in early morning hours and in the evenings and every 10
minutes in the daytimes. The only exception is line F which runs every 10 minutes in the morning hours before rush hour and evening. In the daytimes it runs every 5 minutes like in S20.

Afterwards, the existing S-train lines in the timetable for the original Trafikplan 2032 have to be cancelled. This is done with the tool Transit Data Scenario Manager, in which a specific Line, Line variant, Schedule and Run can be selected or unselected depending on including the specified line or train in the model. Due to the inheritance-procedure according to Figure 60, a Run cannot be selected, if the relevant Schedule is unselected.

6.3.1 New bus network

After the implementation of the new railway line in Copenhagen, it could be relevant to investigate the current network of buses in the model. Some lines may be parallel to the Express Tunnel and since the new tunnel might reduce the travel time significantly from southern parts to the northern parts and in the opposite direction in the network, passengers will move to the S-train instead of using the existing bus. It means that the bus network should be adapted to the Express Tunnel as it was done for the new metro line Cityringen. However, since the bus network in LTM currently is not update to the existing network, it is considered to be difficult to find the right current lines in the network.

Hence, the bus network is not adapted to the new tunnel, but for further investigations it would be necessary to consider it for saving operational costs for the buses.

6.4 Scenario runs

On the basis of the new sub-scenarios 101 and 102, the main scenarios 101 and 102 have to be created, and these will also include the road network, the freight network and air network. Furthermore, the most important model for the main scenario besides the public network model is the demand model.

It is assumed, that the Express Tunnel is opened in 2030 which means that the main scenario has to include sub-scenarios for 2030 or at least at closest to this year.

The public network model is one sub-model in the main scenario. In order to specify this network, 5 sub-scenarios have to be included. The scenarios Public change scenario and Public connector scenario are scenarios with public changes and connectors, and the scenarios 101 or 102 for Scenario 1 and Scenario 2 are used for these. Public route scenario includes the timetables for the public transport and, therefore, the level of service for the main scenario. The scenario Station matrix scenario includes a station matrix from the year 2010, whereas the scenario Public configurations only indicates, if it should be free to bring bikes in S-trains. It is in this project assumed that free bikes in S-trains will continue.

The demand model includes different scenarios which delivers other information to the main scenario. For this project, the most important scenarios is ownership of cars, number of jobs in zones and population size. These quantities are extrapolated to specific years, and the year 2030 is selected. Furthermore, the demand model includes data about public
fares defined as the monetary cost for trips with the public transport, whereas the scenario Zone Scenario describes parking costs and hotel capacity in the different zones.

The following sub-scenarios are included in the main scenarios 101 and 102:

- **Road network model:**
  - Road Infrastructure scenario: Base 2028
  - Road filter scenario: 0 – No filters
  - Road driving costs: Base 2030
  - Road path finder: 0 – Base case

- **Public network model:**
  - Public change scenario: 101/102 – Scenario 1/Scenario 2
  - Public connector scenario: 101/102 – Scenario 1/Scenario 2
  - Public route scenario: 101/102 – Scenario 1/Scenario 2
  - Station matrix scenario: 0 – 2010
  - Public configurations: 1 – Free bikes in S-trains

- **Freight model:** Base 2010

- **Air model:** Base 2010

- **Demand model:**
  - Freight cost: Base 2010
  - Pas Dem. Ownership Car: Base 2030
  - Pas Dem Job Scenario: Base 2030
  - Population: Base 2030
  - Public fare: Base 2030
  - Road freight: Base 2010
  - Terminal: Base 2010
  - Zone Scenarios: Base 2030

**6.5 Results**

After the route choice calculations, an output calculation in LTM Manager is necessary to run. With the output calculations, it is possible to extract results from the specific scenario and as additional difference output. With a difference output, it is necessary to specify a reference scenario. It means that if a difference between the basis – Trafikplan 2032 – and Scenario 1 or Scenario 2 should be investigated and analysed, it has also been necessary to run a route calculation for Trafikplan 2032 in advance.

The main outputs from Scenario 1 and Scenario 2 – or 101 and 102 in LTM Manager respectively – are the results about the passenger load, i.e. the number of boarding and alighting passengers, on the new stations in the Express Tunnel. Furthermore, it is also relevant to investigate, if the passengers in the network use the new stations for arriving or depart from a zone (in this case to and from a centroid) and/or as an interchange to
other public transport modes. In Table 10 below, the main results from the new stations are listed.

As observed in Table 10, Scenario 1 has only two new stations from where Vibenshus Runddel is highly utilised for passengers, which change to Cityringen (M3), as well as for passengers towards the northern parts of the urban areas Nørrebro and Østerbro. Fewer passengers from Vibenshus Runddel has Rigshospitalet and the inner part of Østerbro as destination or starting point. Furthermore, a high share of the passengers change to the buses at the station.

<table>
<thead>
<tr>
<th>New station</th>
<th>Scenario 1 (101)</th>
<th>Scenario 2 (102)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vibenshus Runddel</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Passengers, S-train</td>
<td>50,512</td>
<td>33,954</td>
</tr>
<tr>
<td>- Changes to metro (M3)</td>
<td>12,129</td>
<td>10,995</td>
</tr>
<tr>
<td>- Changes to bus</td>
<td>8,369</td>
<td>836</td>
</tr>
<tr>
<td>- Connector load Ydre Østerbro V</td>
<td>10,954</td>
<td>10,022</td>
</tr>
<tr>
<td>- Connector load Ydre Nørrebro N</td>
<td>8,568</td>
<td>7,340</td>
</tr>
<tr>
<td>- Connector load Rigshospitalet</td>
<td>3,077</td>
<td>0</td>
</tr>
<tr>
<td>- Connector load Indre Østerbro N</td>
<td>3,389</td>
<td>2,209</td>
</tr>
<tr>
<td>Rigshospitalet</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Passengers, S-train</td>
<td></td>
<td>60,891</td>
</tr>
<tr>
<td>- Changes to bus</td>
<td></td>
<td>2,929</td>
</tr>
<tr>
<td>- Connector load Rigshospitalet</td>
<td></td>
<td>39,368</td>
</tr>
<tr>
<td>- Connector load Indre Nørrebro S</td>
<td></td>
<td>17,360</td>
</tr>
<tr>
<td>Forum</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Passengers, S-train</td>
<td>62,793</td>
<td>53,331</td>
</tr>
<tr>
<td>- Changes to metro (M1 and M2)</td>
<td>28,710</td>
<td>31,803</td>
</tr>
<tr>
<td>- Changes to bus</td>
<td>2,144</td>
<td>2,044</td>
</tr>
<tr>
<td>- Connector load Indre Nørrebro S</td>
<td>10,596</td>
<td>0</td>
</tr>
<tr>
<td>- Connector load Ydre Nørrebro V</td>
<td>3,108</td>
<td>3,430</td>
</tr>
<tr>
<td>- Connector load Frederiksberg Øst N</td>
<td>4,744</td>
<td>3,998</td>
</tr>
<tr>
<td>- Connector load Frederiksberg Øst Ø</td>
<td>11,081</td>
<td>10,232</td>
</tr>
</tbody>
</table>

Table 10: Main results for the new stations in the Express Tunnel in Scenario 1 and Scenario 2. Rigshospitalet exists only in Scenario 2.

In the meantime, Forum Station has more passengers than Vibenshus Runddel, but almost the half of the passengers change to the metro lines M1 and M2 and fewer to the buses. The station is also the main station for passengers, who have an inner part of Nørrebro as well as the eastern part of the municipality of Frederiksberg as destination.

In Scenario 2, Rigshospitalet Station is added. As a consequence, the connector from Vibenshus Runddel to Rigshospitalet is not used by any passengers and passengers do not change to the buses in the same way as before. It is also observed that Rigshospitalet is the largest station among the three stations in Scenario 2 in relation to the number of
passengers. Hereby, it is also confirmed that many passengers actually have Rigshospitalet as destination and starting point since the connectors are densely loaded. The station at Rigshospitalet has also consequences for Forum Station since the passenger load is lower and Rigshospitalet is the final station for passengers traveling to and from inner Nørrebro – the connector load between Forum and the zone “Indre Nørrebro S” is 0. However, it still remain as an important interchange station for passengers changing from the S-train to the metro.

Further stations in the network have also been investigated, since these stations would be interchange stations after the implementation of the Express Tunnel. Furthermore, Copenhagen Central Station, Nørreport and Østerport are also added since these stations today are interchange stations for passengers changing between the S-train and the metro lines in the inner parts of Copenhagen. The similar results are listed in Table 11 below.

<table>
<thead>
<tr>
<th>Existing station</th>
<th>Basis</th>
<th>Scenario 1</th>
<th>Scenario 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Valby</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Passengers, S-train</td>
<td>28,849</td>
<td>49,272</td>
<td>53,229</td>
</tr>
<tr>
<td>- Changes to regional train and IC</td>
<td>3,666</td>
<td>6,315</td>
<td>8,895</td>
</tr>
<tr>
<td>Ny Ellebjerg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Passengers, S-train + re-train</td>
<td>26,662</td>
<td>35,617</td>
<td>37,430</td>
</tr>
<tr>
<td>- Changes to KR-node (re-train)</td>
<td>81</td>
<td>179</td>
<td>401</td>
</tr>
<tr>
<td>- Changes to line F</td>
<td>6,147</td>
<td>6,130</td>
<td>6,840</td>
</tr>
<tr>
<td>- Changes to metro</td>
<td>2,526</td>
<td>4,841</td>
<td>4,804</td>
</tr>
<tr>
<td>Emdrup</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Passengers, S-train</td>
<td>3,783</td>
<td>6,633</td>
<td>6,371</td>
</tr>
<tr>
<td>Hellerup</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Passengers, S-train (excl. line F)</td>
<td>26,780</td>
<td>34,124</td>
<td>33,097</td>
</tr>
<tr>
<td>- Changes to line F</td>
<td>4,973</td>
<td>3,669</td>
<td>3,864</td>
</tr>
<tr>
<td>- Changes to regional train</td>
<td>2,572</td>
<td>4,015</td>
<td>3,484</td>
</tr>
<tr>
<td>Copenhagen Central Station</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Passengers, S-train</td>
<td>48,820</td>
<td>32,017</td>
<td>33,065</td>
</tr>
<tr>
<td>- Changes to metro</td>
<td>6,953</td>
<td>2,864</td>
<td>3,016</td>
</tr>
<tr>
<td>- Changes to regional and IC</td>
<td>16,806</td>
<td>12,156</td>
<td>11,892</td>
</tr>
<tr>
<td>Nørreport</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Passengers, S-train</td>
<td>78,066</td>
<td>46,037</td>
<td>44,432</td>
</tr>
<tr>
<td>- Changes to metro</td>
<td>21,886</td>
<td>8,463</td>
<td>9,066</td>
</tr>
<tr>
<td>- Changes to regional and IC</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Østerport</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Passengers, S-train</td>
<td>19,725</td>
<td>9,813</td>
<td>9,796</td>
</tr>
<tr>
<td>- Changes to metro</td>
<td>4,666</td>
<td>1,288</td>
<td>1,180</td>
</tr>
<tr>
<td>- Changes to regional and IC</td>
<td>1,049</td>
<td>501</td>
<td>484</td>
</tr>
</tbody>
</table>

Table 11: Results for other important stations in the S-train network.
It is observed in the table, that the main interchange stations today between the S-train, metro and regional trains will get a much lower passenger number, whereas it will increase significantly for Hellerup, Valby and Ny Ellebjerg. Please note that the passenger number at Ny Ellebjerg also includes several passengers from the regional and intercity trains, since these are modelled to stop at the S-train node and, as a consequence, it is not possible to identify the passengers that change between long-distance trains and S-trains if the line variants are modelled in the same node. Another regional train node is named “Ny Ellebjerg (KR-banen)” which includes stops from other regional trains on the new Copenhagen-Ringsted line.

Furthermore, the number of passengers in the railway network in the central parts of Copenhagen has been identified. These results from Scenario 1 are illustrated in Figure 62 below.

The map illustrates that the Express Tunnel in general use the new tunnel instead of the existing tunnel via Nørreport. The links via Nørreport also includes the passengers from the regional trains.

For Scenario 2, a similar map has been drawn. The only difference between those is that it includes the station at Rigshospitalet. However, the number of passengers in the Express Tunnel is changed significantly. These results are illustrated in Figure 63.
As observed on the map, a passenger increase is expected from the southern radial lines towards Forum and Rigshospitalet. However, the number of passengers towards Vibenshus Runddel is reduced and it is considered that these numbers agree with the passenger loads from Table 10.

Differential maps from the basis scenario to Scenario 1 and Scenario 2 have also been produced. These maps illustrate the absolute and relative differences in the number of passengers in the network after the construction of the Express Tunnel. The maps are illustrated in Appendix 6 and Appendix 7 for Scenario 1 and Scenario 2 respectively. The unit for the differential maps is annual average weekday traffic (AAWT).

In general, the differential maps illustrate that some lines experience a significant increase in the number of passengers. This is especially the case for the inner parts of the radial lines, e.g. Ballerup-Valby, Buddinge-Emdrup and Glostrup-Valby. In the meantime, a significant passenger increase is also observed on the metro line Forum-Nørreport, which probably is a consequence of the S-train lines E, H and K now stop at Forum instead of Nørreport.
In the meantime, the passenger load on other lines in the network is reduced significantly. This is especially the case for the line Hellerup-Svanemøllen-Dybbølsbro, since a new alternative is established and fewer trains in the Boulevard Tunnel. Other lines with a reduced passenger load is Ringbanen/line F between Hellerup and Ny Ellebjerg as well as the new light rail line on Ring 3. Furthermore, the passenger load on the Hillerød-branch line is also reduced, primarily because that the number of trains on this line is not raised compared to the other lines. Results from S-train and metro are listed in Table 12.

<table>
<thead>
<tr>
<th>Existing S-train line</th>
<th>Scenario 1</th>
<th>Scenario 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hoje Taastrup-Carlsberg (incl. Valby)</td>
<td>28,973</td>
<td>33,108</td>
</tr>
<tr>
<td>- Absolute difference</td>
<td>27.4</td>
<td>31.3%</td>
</tr>
<tr>
<td>Frederikssund-Langgade</td>
<td>5,427</td>
<td>12,437</td>
</tr>
<tr>
<td>- Absolute difference</td>
<td>5.3%</td>
<td>12.2%</td>
</tr>
<tr>
<td>Køge-Sydhavn (incl. Ny Ellebjerg)</td>
<td>11,177</td>
<td>15,529</td>
</tr>
<tr>
<td>- Absolute difference</td>
<td>10.2%</td>
<td>14.1%</td>
</tr>
<tr>
<td>Farum-Ryparken</td>
<td>7,603</td>
<td>5,741</td>
</tr>
<tr>
<td>- Absolute difference</td>
<td>18.4%</td>
<td>13.9%</td>
</tr>
<tr>
<td>Hillerød-Bernstorffsvej</td>
<td>-3,762</td>
<td>-4,636</td>
</tr>
<tr>
<td>- Absolute difference</td>
<td>-4.4%</td>
<td>-5.4%</td>
</tr>
<tr>
<td>Klampenborg-Hellerup (excl. line F)</td>
<td>8,032</td>
<td>7,449</td>
</tr>
<tr>
<td>- Absolute difference</td>
<td>21.6%</td>
<td>20.0%</td>
</tr>
<tr>
<td>Svanemøllen-Dybbølsbro</td>
<td>-81,703</td>
<td>-82,632</td>
</tr>
<tr>
<td>- Absolute difference</td>
<td>-38.4%</td>
<td>-38.8%</td>
</tr>
<tr>
<td>Hellerup-Ny Ellebjerg (Ringbanen)</td>
<td>-17,772</td>
<td>-16,173</td>
</tr>
<tr>
<td>- Absolute difference</td>
<td>-20.1%</td>
<td>-19.1%</td>
</tr>
<tr>
<td>Metro line M1+M2</td>
<td>18,745</td>
<td>10,270</td>
</tr>
<tr>
<td>- Absolute difference</td>
<td>4.1%</td>
<td>2.3%</td>
</tr>
<tr>
<td>Metro line M3 + M4</td>
<td>-2,357</td>
<td>-6,333</td>
</tr>
<tr>
<td>- Absolute difference, M3 + Nordhavn</td>
<td>-0.4%</td>
<td>-1.1%</td>
</tr>
<tr>
<td>- Absolute difference, Sydhavnsmetroen</td>
<td>2,194</td>
<td>1,964</td>
</tr>
<tr>
<td>- Relative difference, Sydhavnsmetroen</td>
<td>4.9%</td>
<td>4.4%</td>
</tr>
</tbody>
</table>

Table 12: Results from different lines in the S-train and metro network.

In Table 13 the passenger load measured in passenger km and passenger hours for 24 hours in the model.
### Table 13: Passenger loads for different transport modes in the public transport network.

<table>
<thead>
<tr>
<th>Transport Mode</th>
<th>Scenario 1</th>
<th>Scenario 2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>S-train</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Difference, passenger km</td>
<td>202,525 (4.87%)</td>
<td>354,431 (8.52%)</td>
</tr>
<tr>
<td>- Difference, passenger hours</td>
<td>-85 (-0.10%)</td>
<td>4,552 (5.16%)</td>
</tr>
<tr>
<td><strong>Regional train, DSB</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Difference, passenger km</td>
<td>-61,521 (-1.31%)</td>
<td>-3,310 (-0.07%)</td>
</tr>
<tr>
<td>- Difference, passenger hours</td>
<td>-676 (-1.19%)</td>
<td>-232 (-0.41%)</td>
</tr>
<tr>
<td><strong>Regional train, Arriva</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Difference, passenger km</td>
<td>-808 (-0.09%)</td>
<td>-1,607 (-0.17%)</td>
</tr>
<tr>
<td>- Difference, passenger hours</td>
<td>-8 (-0.06%)</td>
<td>-19 (-0.14%)</td>
</tr>
<tr>
<td><strong>Long-distance train (IC and IC-lyn)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Difference, passenger km</td>
<td>-50,796 (-0.36%)</td>
<td>-100,777 (-0.72%)</td>
</tr>
<tr>
<td>- Difference, passenger hours</td>
<td>234 (0.22%)</td>
<td>-123 (-0.11%)</td>
</tr>
<tr>
<td><strong>Local train and light rail</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Difference, passenger km</td>
<td>-41,814 (-4.74%)</td>
<td>-33,390 (-3.85%)</td>
</tr>
<tr>
<td>- Difference, passenger hours</td>
<td>-1,080 (-5.38%)</td>
<td>-833 (-4.14%)</td>
</tr>
<tr>
<td><strong>Bus</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Difference, passenger km</td>
<td>-126,210 (-1.91%)</td>
<td>-142,303 (-2.15%)</td>
</tr>
<tr>
<td>- Difference, passenger hours</td>
<td>-5,699 (-2.83%)</td>
<td>-6,582 (-3.27%)</td>
</tr>
<tr>
<td><strong>Long-distance coach</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Difference, passenger km</td>
<td>6,372 (4.08%)</td>
<td>5,474 (3.50%)</td>
</tr>
<tr>
<td>- Difference, passenger hours</td>
<td>98 (5.02%)</td>
<td>84 (2.97%)</td>
</tr>
<tr>
<td><strong>Metro</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Difference, passenger km</td>
<td>73,324 (3.04%)</td>
<td>51,848 (2.18%)</td>
</tr>
<tr>
<td>- Difference, passenger hours</td>
<td>3,206 (5.02%)</td>
<td>3,151 (4.93%)</td>
</tr>
<tr>
<td><strong>Ferries</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Difference, passenger km</td>
<td>59 (0.04%)</td>
<td>96 (0.06%)</td>
</tr>
<tr>
<td>- Difference, passenger hours</td>
<td>8 (0.12%)</td>
<td>11 (0.16%)</td>
</tr>
</tbody>
</table>

In general, the results from the tables illustrate that the passenger load in the S-trains grow significantly with the Express Tunnel and the new network of lines. This is also expected since the service on some of the radial lines is increased and the new tunnel leads to significant reductions in travel time in the public network.

However, the passenger load in the regional trains and in the intercity trains is expected to decrease. It might a consequence from an improved S-train service on the radial lines or from new connections in the network. One of the consequences is, for instance, that some of the lines do not serve Copenhagen Central Station from where the majority of the long-distance trains depart.

It is also expected that the passenger load in the bus network is decreased. This is a consequence from the new tunnel, which improves the average travel speed through the inner parts of Copenhagen. Furthermore, a new station at Rigshospitalet is also expected to be a reason for fewer bus passengers since these will take the S-train instead.
The passenger load for the metro lines is also increased significantly, and the increase is more significant in Scenario 1 than in Scenario 2. It also makes sense by comparison with the passenger numbers in Table 12.

According to the maps in the appendices, it seems like that Scenario 2 leads to a more significant increase in passenger load than Scenario 1. The socio-economic consequences from the scenarios and from changing the S-train network are analysed in the next chapter.

7 Socio-economic analysis
This chapter introduces the socio-economic analysis on the basis of the findings and results from the previous chapters. The analysis is conducted as a cost-benefit-analysis (CBA) in the Excel sheet TERESA from the Ministry of Transport and Housing since this sheet is specifically applied to transport projects and since results from LTM can be pasted directly into the sheet.

The subchapters gives an overview of the procedure on how to calculate the costs and benefits and how these are applied to the CBA. Therefore, the different methods are described in detail in every subchapter.

7.1 Construction budget
The primary cost for the Express Tunnel including upgrading of the depot track at Åmarken with new turnouts or points depending on the choice of Scenario 1 or Scenario 2 is the construction budget. The construction budget of a railway project is included in the plan for the carrying-out or construction of the project, which primarily are based on the following five phases according to the Ministry of Transport and Housing:

- Definition – preliminary investigations
- Program – basis for decision
- Design – detailed project
- Tender process
- Closing – carrying out and commissioning

The Definition-phase is a phase for preliminary investigations and its purpose is “to examine and find all options that will fulfil an identified need. Overall delimitation of the project and tender project” and to make preliminary investigations. The goal is to present a number of alternative solutions and an overall description of alternatives. This phase can form a basis for decision at the relevant level or at least present a bill for the program budget. In the end, a choice between the presented alternatives is made and a go/no-go decision for the program phase.

The next phase is the program-phase. This provides a technical basis for the project and includes a thorough description of all elements that are necessary to make a final decision. The phase is ended with an updated project plan and an approval of the project.
If the project is adopted in the program-phase, the remaining three phases include a detailed project design, tendering processes and the carrying-out of the project. However, the separation between these phases are not as clear as between the definition- and program-phase since different parts of the project can be constructed in different phases (Ministry of Transport and Housing, 2017).

Since this report is an overall description and analysis of the Express Tunnel, it is consequently assumed to be based on the definition-phase. In this case, the guideline and method for estimating a construction budget in this phase will be the overall method for the construction budget for Scenario 1 and Scenario 2. In this case, the construction budget will be based on the illustrated guideline in Figure 64 below.

Figure 64: Overview of the estimation of a construction budget for the definition-phase (phase 1) and the program-phase (phase 2).

Figure 64 illustrates that the construction budget consists of the sum of quantities multiplied with their respective unit prices and then added to a price of special structures and special risks. The sum results in a basis budget, and in phase 1 a correctional reserve by 50% has to be added to the basis budget. The overall procedure is called New Budgeting Principles – NBP\(^{13}\) (Heydari, 2019). The quantities, which have to be multiplied by their respective unit price, are illustrated in the diagram in Figure 65 below.

Figure 65: Overview of the grouping process for estimating construction budgets (Heydari, 2019).

The different quantity categories are filled out according to the railway project and if the railway project does not concern a specific category, this is not included in the basis budget. Since the project is on an early stage it has not been possible to consider all groups. The groups “Civil works”, “Land/area”, “Forestry” as well as “Other” are not considered in this project, since elements from these groups do not apply to this early estimation.

\(^{13}\) In Danish it is abbreviated NAB for Ny Anlægsbudgettering.
The first main group from Figure 65 is Track. This entry includes all elements related to the construction of the track in the Express Tunnel. The track type, Slab-track or ballastless track, is selected as the primary track type in the Express Tunnel. For track construction in tunnels, this type is an advantage since the cross section for the tunnel elements, say the diameter, can be smaller due to the lower construction height for slab-track compared to ordinary ballasted track (Jochim & Lademann, 2018). Furthermore, another advantage with slab-track is its long life-cycle. The maintenance of this track type can be reduced when it is compared to ballasted track. Especially this property is an advantage for railway lines with a dense traffic volume and short headways (Fiedler & Scherz, 2012). However, the construction expenses with slab-track are higher than with ballasted track, and in order to investigate the application of slab-track compared to ballasted track for railway lines it is necessary to determine if the track should have high capital costs with less maintenance costs or lower capital costs with higher maintenance costs. In this case, the use of slab-track compared to ballasted track on the new high-speed line between Copenhagen and Ringsted was considered. The high capital costs as well as the long reimbursement period was the primary reason for choosing ballasted track on this line. With this investigation, Banedanmark estimated the capital cost of slab-track to be 2.5 times the price of ballasted track. Today, the Boulevard Tunnel between Østerport and Vesterport for S-trains and regional trains as well as some other tunnels and bridges are equipped with slab-track (Banedanmark, 2016). Since the capital cost of slab-track is estimated to be 2.5 times the price of ordinary ballasted track, the unit cost of the slab-track in the tunnel will be estimated on basis of a unit cost of ballasted track.

The three main references for estimating the unit prices for the listed elements are the following undergoing projects:

- New railway line Hovedgård-Hasselager
- New metro line – Havneringen
- New tunnel Helsingør-Helsingborg

Several unit prices for the entries in these construction budgets are listed in different price levels. For the construction budget, these entries need to be presented in the same level in order to compare them, which is done by extrapolating the unit prices with the net price index to the same price level, which is determined as 2019 in this project. An overview of the included track elements in the construction budget is illustrated in Table 14.

<table>
<thead>
<tr>
<th>Track element and Other power</th>
<th>Quantity</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slab-track</td>
<td>22,000 (22,400)</td>
<td>[m]</td>
</tr>
<tr>
<td>Points in tunnel (slab-track)</td>
<td>4</td>
<td>pc.</td>
</tr>
<tr>
<td>Points</td>
<td>10</td>
<td>pc.</td>
</tr>
<tr>
<td>Point machines</td>
<td>14</td>
<td>pc.</td>
</tr>
<tr>
<td>Point heating</td>
<td>10</td>
<td>pc.</td>
</tr>
</tbody>
</table>

Table 14: Overview of track elements and “Other power”.

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Since point heating in Table 14 is the only element belonging to “Other power”, this element is also included in this table. The number in parentheses refers to Scenario 2.

The second entry is Traction power, which includes everything belonging to the traction power for the electric S-trains such as the overhead catenary system, feeder stations and earthing. For the proposed service, COWI suggests\textsuperscript{14} that four feeder stations should be constructed with 2-2.5 km distance between along the line as well as an upgrade of 2 existing feeder stations. The overview of elements is illustrated in Table 15.

\begin{table}[h]
\centering
\begin{tabular}{|l|l|l|}
\hline
\textbf{Traction power} & \textbf{Quantity} & \textbf{Unit} \\
\hline
Overhead catenary system & 22 (22.4) & [km] \\
\hline
Earthing of line & 11 (11.2) & [km] \\
\hline
Earthing of station & 2 (3) & pc. \\
\hline
Feeder stations & 4 & pc. \\
\hline
Upgrade of existing feeder stations & 2 & pc. \\
\hline
\end{tabular}
\caption{Overview of elements for traction power.}
\end{table}

The entry Building covers the costs for the station construction and the excavations for them. Depending on the choice of Scenario 1 or Scenario 2, the number of stations has to be adjusted from 2 to 3.

The stations are in this project assumed to be constructed as centre platforms where a single platform is located between two platform tracks. It means that each station consists of one single wide platform instead of one platform to each track.

The dimensions of the platforms are assumed to follow the standard BN 1-9-2 Sikkerheds-og opholdszoner på perroner by Banedanmark. The length of the platforms should fulfil the required lengths for two coupled SA-units. Since a SA-unit has the length 83.72 m according to Table 1, the length of the platforms is assumed to be 180 m in order to serve two coupled SA-units and a reserve.

The width of the platform is determined by the rules in the standard BN 1-9-2. For S-train platforms, the width of the safety zone from platform edge to the service zone should be 0.75 m to each side. Furthermore, the service zone should be 2.0 m to each side and if it is assumed that facilities have a width by 0.5 m, the total width is 6.0 m. Another expenditures to platform equipment such as ticket machines should also be considered.

Finally, it is decided to include an expenditure to platform screen doors on the platforms. This is included since these already exist on the platforms for the metro and if the S-trains should be autonomous in the future, the new stations should also include the screen doors. The results for stations are illustrated in Table 16.

\textsuperscript{14} After a meeting with the catenary-section.
Stations

<table>
<thead>
<tr>
<th>Stations</th>
<th>Quantity</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Platform</td>
<td>2160 (3240)</td>
<td>[m²]</td>
</tr>
<tr>
<td>Platform edge</td>
<td>720 (1080)</td>
<td>[m]</td>
</tr>
<tr>
<td>Platform screen doors</td>
<td>720 (1080)</td>
<td>[m]</td>
</tr>
<tr>
<td>Platform equipment</td>
<td>2160 (3240)</td>
<td>[m²]</td>
</tr>
<tr>
<td>Elevators</td>
<td>2 (3)</td>
<td>pc.</td>
</tr>
<tr>
<td>Excavations</td>
<td>2 (3)</td>
<td>pc.</td>
</tr>
</tbody>
</table>

Table 16: Overview of elements for stations.

Since this project does not concern the construction of tunnels on a detailed level, a reference for a tunnel cost has been applied to this calculation. The benchmark is a new railway tunnel across Øresund from Helsingør to Helsingborg with data from the Danish Road Directorate, and the prices for the Express Tunnel will be estimated on the basis of this budget. However, two conditions apply to the Express Tunnel:

- The calculation is based on a solution with overhead conductor rails instead of ordinary catenary wires. The advantage of this solution is that it is suitable in constricted space conditions and a more reliable alternative to conventional overhead contact lines. Consequently, the vehicle clearance profile in tunnels can be smaller (Siemens, 2019).
- It is considered that emergency exits in the tunnel should be planned in a way that no location in the tunnel would have be more than 300 m from an emergency exit to and from the tunnel, a platform at stations as well as to tunnel entrances. This is listed as article 30 in the German regulation BOS trab (“Verordnung über den Bau und Betrieb der Straßenbahnen”). This regulation applies to trams and light rail lines as well as metro (in German: U-Bahn) lines but in general not a public transport network such as S-trains. However, this regulation is applied to this project in order to determine a minimum number of emergency exits. When a more detailed design of the tunnel is finished, the number of necessary exits might be reduced.

<table>
<thead>
<tr>
<th>Bridges/structures</th>
<th>Quantity</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tunnel elements</td>
<td>22 (22.4)</td>
<td>[km]</td>
</tr>
<tr>
<td>Excavation for interchange chambers</td>
<td>4</td>
<td>pc.</td>
</tr>
<tr>
<td>Emergency exits</td>
<td>15 (16)</td>
<td></td>
</tr>
</tbody>
</table>

Table 17: Overview of main elements for tunnel.

A unit prices for tunnel elements for the Express Tunnel is based on a construction budget from DTU for a new fixed link between Helsingør and Helsingborg. This fixed link has a primary element – a double-tracked tunnel with two tubes below Øresund with an estimated cost by 9,084 M DKK\(^\text{15}\) incl. a 50% correctional reserve. With a length by 7.7 km

\(^{15}\) In 2019-price level.
an estimated unit price for 1 km tunnel is 1,179.7 M DKK. This tunnel would, however, be constructed for regional and long-distance trains with a different profile from the S-trains. The profile for S-trains will then be 3.6% less compared to the profile for long-distance trains, but an even smaller profile for S-trains with an overhead conductor rail by 7.6% by comparison to the long-distance profile can be obtained.

Finally, it is expected that a bored tunnel in Copenhagen would be cheaper to construct than below Oresund since the water pressure demands higher specifications regarding the cross section in tunnels in order to resist the pressure. Therefore, it is estimated that a further 10% reduction in the unit price can be obtained for the tunnel. The unit price for the tunnel can then be calculated as follows:

\[ 1,179.7 \text{ M DKK} \cdot 0.924 \cdot 0.9 = 981.1 \text{ M DKK} \]

Since this unit price includes a 50% correctional reserve the estimate for a unit price without the reserve would then be 647.5 M DKK by multiplying with 0.66.

The construction budget for the fixed link Helsingør-Helsingborg includes a cost for new tunnel stations which is estimated to 900 M DKK (excl. reserve) for the construction of a new station chamber in Helsingør. This is, however, for longer long-distance trains and it is estimated that a platform length of 180 m for two SA-trainsets should be applied will require a station chamber with an estimated cost by 600 M DKK. The scenarios will require 2 and 3 station chambers depending on Scenario 1 or Scenario 2 and an interchange chamber is estimated to the half of this cost.

The unit prices from the cost estimations for these projects are applied to the estimation of the construction budget for the Express Tunnel. Since these projects are not yet adopted and constructed, the unit prices are confidential and will therefore not be presented in the report. The main entries, which also include a cost for project and construction management with an estimate by 15%, are presented in Table 18 below.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Track (incl. Other power)</td>
<td>289.1</td>
<td>293.4</td>
</tr>
<tr>
<td>2. Traction power</td>
<td>169.2</td>
<td>173.1</td>
</tr>
<tr>
<td>3. Signalling</td>
<td>572.5</td>
<td>572.5</td>
</tr>
<tr>
<td>4. Stations incl. excavation</td>
<td>1,334.4</td>
<td>1,984.3</td>
</tr>
<tr>
<td>5. Tunnel incl. interchange chambers</td>
<td>7,722.6</td>
<td>7,852.0</td>
</tr>
<tr>
<td><strong>Basis budget</strong></td>
<td><strong>10,088</strong></td>
<td><strong>10,875</strong></td>
</tr>
<tr>
<td>Correctional reserve 50%</td>
<td>5,044</td>
<td>5,438</td>
</tr>
<tr>
<td><strong>Total incl. 50%</strong></td>
<td><strong>15,132</strong></td>
<td><strong>16,313</strong></td>
</tr>
</tbody>
</table>

*Table 18: Overview of construction budget for Scenario 1 and Scenario 2.*

It means that Scenario 2 has higher construction costs than Scenario 1 due to the additional station and a longer tunnel.
7.2 Cost-benefit analysis

A cost-benefit analysis (CBA) is a method for evaluating the “goodness” of public investments and for ranking alternative investments (Barfod & Leleur, 2014). The basic method is to compare costs and benefits in the same way since they are measured as monetary units. It means that quantities that normally are measured in other units such as waiting time for public transport now has a monetary value attached to it.

For transport projects, which are characterised by having consequences for e.g. existing or new passengers in the public transport network, a construction phase of the project with net costs in the opening year will later be replaced by net benefits. These are assumed to grow in the following years since the traffic is expected to increase. However, it should be necessary to evaluate the net benefits into single values for indicating if the project is profitable or not. In order to do so, three main indices are applied in the socio-economic analysis. These are:

- Net present value (NPV)
- Internal rate of return (IRR)
- The ratio between NPV and the present value per DKK from public expenditures

The net present value (NPV) is given by:

\[ \text{NPV} = \sum_{t=0}^{T} \left( B_t - C_t \right) \left( 1 + r \right)^{-t} \]

In this formula, \( T \) represents the calculation period and is measured in years. \( B_t \) and \( C_t \) represent the amount of benefits and costs respectively in year \( t \). The sum of benefits and costs in the calculation period is multiplied by the discount factor \( \left( 1 + r \right)^{-t} \) in which \( r \) represents the discount rate. The purpose with the NPV is to aggregate the streams of benefits and costs into one single number. If a project is profitable, the NPV should be positive:

\[ \text{NPV} > 0 \]

The discount factor has to be multiplied to the net benefits, since the discount rate is used to compare all benefits and costs over time in order to make the value of present and future impacts comparable. It can be seen of a rate of interest in that way that it is better to achieve the profit today than tomorrow and the expenditures tomorrow than today. This is used in order to discount the future cash flows back to a present value. In Denmark, the discount rate has been 4% for year 0-35, 3% for 36-70 and 2% after year 70, where year 0 refers to the opening year or the year that benefits and costs have to be discounted back to. In this project, the opening year of the project is defined as 2030, since it is assumed that all new adopted public transport projects are finished in this year.

The second index is the internal rate of return (IRR). The purpose of the IRR is to determine the rate \( i \), which balances the cost and benefit streams. This rate can be determined by the following equation:
\[ \frac{\sum_{t=0}^{T} B_t - C_t}{(1 + r)^i} = 0 \]

In this case, the higher the rate \( i \) gets, the better the examined project. For a profitable project, the rate has to be higher than the discount rate.

The third index is the ratio between NPV and the present value from public expenditures and is determined by the following formula:

\[ \frac{NPV}{\sum_{t=0}^{T} \frac{C_{pub}}{(1 + r)^t}} \]

The public expenditures, \( C_{pub} \), consists of the construction costs, the maintenance costs and the tax revenue. In order for a project to be feasible, this rate should be larger than 0. (Barfod & Leleur, 2014).

Since \( t \) refers to a specific year, a calculation period for the project has to be specified. For a large infrastructure project, such as a new tunnel, it is recommended to use a calculation period equal to 50 years, which is selected in this project as well.

The following primary impacts should be covered in a cost-benefit-analysis:

- **Construction costs**
  The construction costs are determined as in construction budget for Scenario 1 and Scenario 2. This entry is calculated as illustrated in chapter 7.1. It is assumed that the construction costs are distributed over a construction period of 6 years.

- **Nuisance related to construction**
  This impact covers problems with noise, extra traffic or interruption of railways during the construction period. In this project, however, such impacts are with the current knowledge about the construction uncertain and, consequently, it is decided not to include this in the analysis.

- **Maintenance cost**
  The whole construction of the tunnel including new junctions, tracks, catenary and stations has to be maintained in the following years after opening. In the meantime, the level of uncertainty regarding the construction of the tunnel is on the current stage high and it is therefore decided to omit this cost on the current level. However, it would in a new analyses when more certain factors have been investigated further be possible to assume a yearly percentage of the construction cost. This percentage is assumed to be 1.2% of the construction costs for a fixed link across Kattegat as well as a
new tunnel in the orbital road Ring 2 from Nordhavn to Amager\textsuperscript{16}, and this might relevant to assume the same percentage for the Express Tunnel.

- **Scrap value**
The scrap value is a monetary value of the project in the end of the evaluation period. This impact is seen as a benefit and is normally defined as the total construction costs discounted back to the opening year from the end of the evaluation period. This is calculated with the formula

\[ S_T = \frac{C_0}{(1 + r)^T}, \]

from where \( S_T \) is the scrap value, \( C_0 \) is the construction costs and \( T \) the calculation period.

- **Travel time savings**
The travel time savings are important for this project, since the profitability of the Express Tunnel depends on if the passengers will get a travel time benefit. These are defined as the difference in the flow in the before-network and in the after-network or between the basis scenario and Scenario 1 and Scenario 2.

- **Driving costs**
Driving costs are valued cost per driven or flying kilometre. The impacts on flying kilometres are not covered in this project, but for road traffic this cost includes wearing of roads and cars as well as petrol.

- **Taxation consequences**
To finance the public expenditures, it is necessary to collect taxes. It is, however, not free to collect taxes since taxes affect the behaviour of the public which is referred to as a distorting impact. An income tax leads to a reduction in the willingness to work compared to a scenario without an income tax and the labour market will then be decreased. In order to include the tax distortion a specific factor has to be multiplied to the public net expenditures to include the loss for the society as a consequence from the distortion. This factor is called the tax distortion factor, \( \lambda \), and is defined as 20\% as the expenditures. More specially, the tax distortion factor is then 1.20 according to the Ministry of Finance in 1999 (Fosgerau & Pilegaard, Arbejdsudbudseffekter på transportområdet, 2015).

The consequence of collecting distorting taxes is called the labour market distortion which is defined as a cost for the society. This is calculated as the total net costs for the society multiplied by the tax distortion factor.

A benefit for the society is, however, also obtained from other labour market impacts. This is obtained from changes in the generalised transport costs for commuters and business

\textsuperscript{16} In correspondence with Henrik Sylvan, DTU.
passengers as well as for freight transport. It is a benefit since the new project increases the
ingenuity to work.

Other taxation consequences for the society will also apply if new passengers change from
car to public transport after implementation of the project. It means that taxation collected
from petrol- and diesel will be decreased and this is therefore listed as a cost for the
society (Ministry of Transport, 2015).

The socio-economic analysis should, furthermore, be presented in market prices or user
prices which are the basis for the preferences by the public and takes the willingness to
pay for a specific service into account including taxes. For converting the entries in factor
prices, i.e. prices without taxes, to market prices the net taxation factor, NAF (Danish for
nettoafgiftsfaktoren), has to be multiplied with the factor prices. This factor is defined as the
ratio between the gross domestic product (GDP) and the gross factor income (GFI) and has
the value 1.325 (Barfod & Leleur, 2014).

- External impacts

External impacts for the CBA consists in general of four main groups: Noise, accidents,
local air pollution and climate pollution. The impact noise is calculated on the basis of a
Noise Load Number, SBT, (in Danish Støjbelastningstal) multiplied by a unit price per SBT.
Accidents are calculated on the basis of driven km and is divided into mild injuries, severe
injuries and fatal injuries. Each group has a specific unit price.
The unit prices for the above-mentioned groups can be found in the sheet
Transportøkonomiske Enhedspriser.

7.2.1 Travel time savings

One of the main purpose with the Express Tunnel is to reduce the travel time for the
passengers in the public transport network. Since these savings are one of the major
impacts for evaluating the profitability of the tunnel, it is necessary to assign a monetary
value on them.

The travel time savings will result in a consumer surplus which can be defined as a
monetary value from the benefits such as reduced travel time, waiting time and changing
time. Since the generalised cost with the travel time reduction is decreased from $c_0$ to $c_1$,
the demand for the good is expecting to increase from $N_0$ to $N_1$. Since the generalised costs
can be defined as a function of demand with a demand curve, the existing passengers in
the network will experience the complete reduction in generalised costs whereas new
passengers from the increased demand will experience the half of it. This rule is called the
Rule-of-a-half, and in Figure 66 below, this curve is illustrated.
The shaded area in Figure 66 illustrates the consumer surplus from the increased demand with decreased generalised costs. The area A illustrates the existing passengers whereas the area B is the new passengers from other modes like car or car passenger or new passengers who would not make a trip before the decrease. The new demand is \( N_1 \) and with an approximation, the area B can be compared to the area of a triangle. According to the rule-of-a-half, the new passengers will only obtain the half cost saving whereas the existing passengers will obtain the full cost saving.

First and foremost, the monetary value depends on the passenger type. In the assignment model in LTM, the passengers are divided up into three main groups: Commuting, Business and Other. The monetary value for these groups are differentiated, since a Business trip has a higher monetary value than a Commuting and Other trip. Moreover, the monetary value also depends the type of time. In this case, the travel time savings are divided into the following types:

- Vehicle time
- Waiting time
- Delays
- Access and egress time
- Changing time
- Hidden waiting time
- Number of changes

For each type, a unit prices per passenger hour depending of the three groups and on the type of time has to be multiplied by the total passenger hours. The unit prices in this project are from the sheet *Transportøkonomiske Enhedspriser*. However, since the public assignment model is based on the schedule and congestion and delays is omitted, LTM does not calculate congestion time and this time will not be included in the CBA.
Based on the findings from LTM in Table 19, the travel time savings are significantly higher for Scenario 2 than from Scenario 1. It is observed that the vehicle time and waiting time are slightly higher in Scenario 1 than Scenario 2, whereas Scenario 2 has a benefit from access and egress time as well as for number of changes. However, the general conclusion is that even though the passengers in the Express Tunnel will gain a longer travel time with the station at Rigshospitalet, the additional station has a better influence on the entire network since the travel time savings (in DKK) are much higher.

### 7.3 CBA in TERESA

The cost-benefit-analysis for this project is compiled in the Excel sheet TERESA (Transportministeriets Regnearksmodel for Samfundsøkonomisk Analyse for transportområdet), which is developed by Incentive for the Ministry of Transport and Housing to be applied for a CBA within the transport sector. In this sheet, the information about the project in detail is typed and it is also possible to type all benefits and costs for the project and to specify the opening year, price level and construction period. The unit prices for travel time savings, operation and maintenance costs, and external impacts are also included in the sheet which means that these have to be multiplied with the results measured in time or in other non-monetary units.
Moreover, in the version 5.07 it is possible to copy the results from LTM regarding the savings in travel time and ticket revenue directly into the sheet. For this purpose, LTM creates outputs specifically designed to copy into TERESA and calculates the savings based on a year and not only for one day as in the model.

<table>
<thead>
<tr>
<th>Results from CBA (2019-level, M DKK, present values)</th>
<th>Scenario 1</th>
<th>Scenario 2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Construction costs</strong></td>
<td>-15,132</td>
<td>-16,313</td>
</tr>
<tr>
<td>Scrap value</td>
<td>2,344</td>
<td>2,527</td>
</tr>
<tr>
<td><strong>Operation and maintenance costs</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ticket revenue, public transport</td>
<td>633</td>
<td>2,571</td>
</tr>
<tr>
<td>Road pricing</td>
<td>672</td>
<td>2,568</td>
</tr>
<tr>
<td><strong>User impacts</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Travel time savings, road traffic</td>
<td>2,999</td>
<td>3,483</td>
</tr>
<tr>
<td>Travel time savings, public transport</td>
<td>569</td>
<td>-115</td>
</tr>
<tr>
<td>Driving costs, road traffic</td>
<td>2,401</td>
<td>3,483</td>
</tr>
<tr>
<td>Road pricing</td>
<td>33</td>
<td>-23</td>
</tr>
<tr>
<td><strong>External impacts</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Accidents</td>
<td>35</td>
<td>33</td>
</tr>
<tr>
<td>Noise</td>
<td>21</td>
<td>20</td>
</tr>
<tr>
<td>Local air pollution</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Regional air pollution (climate)</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td><strong>Other impacts</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Taxation consequences</td>
<td>-1,641</td>
<td>-2,050</td>
</tr>
<tr>
<td>- Labour market distortion</td>
<td>-199</td>
<td>-635</td>
</tr>
<tr>
<td>- Labour market benefit</td>
<td>-1,505</td>
<td>-1,489</td>
</tr>
<tr>
<td><strong>Net present value (NPV)</strong></td>
<td>-10,885</td>
<td>-9,870</td>
</tr>
<tr>
<td><strong>Internal rate of return (IRR)</strong></td>
<td>0.9%</td>
<td>1.4%</td>
</tr>
<tr>
<td><strong>Ratio between NPV and the present value from public expenditures</strong></td>
<td>Negative</td>
<td>Negative</td>
</tr>
</tbody>
</table>

Table 20: Main results from the CBA in TERESA. Only main entries are presented.

From Table 20 it is observed, that the scrap value is higher for Scenario 2 compared to Scenario 1 since the construction costs are higher. It is also observed that the ticket revenue from the public transport is much higher in Scenario 2 which means that this scenario attracts more passengers by comparison to Scenario 1. The attraction of new passengers is probably caused by the higher travel time savings for Scenario 2. It means that the passengers in the entire network saves more travel time than in Scenario 1 even though that an additional station is built.

Furthermore, external impacts from the cars have a positive sign which means that these are a benefit from fewer km in the network. However, the present value for this entry is small and it indicates that not many car drivers will use the public transport instead after the implementation of the new tunnel. This is also indicated on the differential maps in Appendix 6 and 7 – only on the orbital roads in the Greater Copenhagen Area a small
decrease in the number of cars measured in AAWT is observed. It can then be concluded that the Express Tunnel has a primary benefit from travel time savings for passengers in the public transport.

It can also be concluded that since the NPV and IRR are higher for Scenario 2 compared to Scenario 1, Scenario 2 is the most profitable scenarios even though that the construction costs are higher for this scenario. However, none of the scenarios are socio-economically profitable since the NPV for both scenarios is negative and the IRR is below the discount rate. The ratio between NPV and the present value from public expenditures is consequently negative since the NPV is negative.

In order to test the uncertainty of some significant factors in the CBA, some sensitivity analyses have been conducted. One of the most significant factors in this project is the travel time savings and it is tested how much an increase or a decrease of this factor will affect the probability.

Other analyses regarding an omission of new generated passengers in the public transport network as well of an analyses of so-called optimism biases are also performed. Optimism biases are explained in more details in chapter 8.7. It is possible to conduct these sensitivity analyses in TERESA and the results from them are listed in Table 21 below.

<table>
<thead>
<tr>
<th>Sensitivity analyses (2019-level, M DKK)</th>
<th>Scenario 1 IRR</th>
<th>Scenario 2 IRR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Values for travel time savings</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- High values, +25%</td>
<td>1.1%</td>
<td>1.6%</td>
</tr>
<tr>
<td>- Low values, -25%</td>
<td>-0.7%</td>
<td>1.1%</td>
</tr>
<tr>
<td>Omission of new passengers</td>
<td>1.0%</td>
<td>1.0%</td>
</tr>
<tr>
<td>Optimism bias, low and high</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Optimism bias 50%</td>
<td>1.0%</td>
<td>1.5%</td>
</tr>
<tr>
<td>- Optimism bias 80%</td>
<td>0.8%</td>
<td>1.3%</td>
</tr>
</tbody>
</table>

Table 21: Results from sensitivity analyses.

As observed in the table, the change in values for travel time savings has the biggest impact on the net present value and the internal rate of return. With an increase and a decrease by 25% and -25% respectively result in an interval in the IRR by 0.7% to 1.1% for Scenario 1 and by 1.1% to 1.6% for Scenario 2. With the omission of new generated passengers from Scenario 1 and Scenario 2, the IRR will almost be equal but since Scenario 2 still has the highest net present value, it is still more profitable which is also the case among the different sensitivity analyses.

However, both scenarios remain socio-economically unprofitable which means that the benefits from especially travel time savings do not exceed the costs.
8 Discussion

From the final results in the CBA it is concluded that the project is not socio-economically profitable since the benefits are not higher than the costs. It is also noticeable that some radial lines have a decrease in the number of passengers even though that the travel time to and from other lines in the public transport network is decreased. This chapter discusses the results with the methodology and recommends ideas for further analyses based in the results.

8.1 Low utilisation of both tunnels

One of the main disadvantages with the proposed operation is the low utilisation of the Boulevard Tunnel and the Express Tunnel. The total number of trains in the tunnels in Copenhagen is raised from 30 in S20 to 42 with the new scenarios with 24 trains per hour in each direction in the Boulevard Tunnel and with 18 in the Express Tunnel and the following capacity consumptions as illustrated in Table 22 in both tunnels are calculated.

<table>
<thead>
<tr>
<th>Capacity consumption in the S-train tunnels</th>
<th>Basis</th>
<th>Scenario 1</th>
<th>Scenario 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boulevard Tunnel (Sam-Dbt)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Northbound</td>
<td>71.8%</td>
<td>55.2%</td>
<td>55.2%</td>
</tr>
<tr>
<td>Southbound</td>
<td>70.3%</td>
<td>54.2%</td>
<td>54.2%</td>
</tr>
<tr>
<td>Express Tunnel (Cbn-Vhr)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Northbound</td>
<td>-</td>
<td>39.3%</td>
<td>53.2%</td>
</tr>
<tr>
<td>Southbound</td>
<td>-</td>
<td>40.9%</td>
<td>49.7%</td>
</tr>
</tbody>
</table>

Table 22: Capacity consumption in the Boulevard Tunnel and the Express Tunnel.

It is observed in Table 22 that the capacity consumption in the Boulevard Tunnel is reduced significantly and now below UIC max in daytime which is illustrated in Figure 49 as well. It is also observed that the capacity consumption in the Express Tunnel is increased in Scenario 2 compared to Scenario 1 which is a result from the additional stop at Rigshospitalet. With this stop the S-trains occupy the tunnel for a longer time and the theoretical minimum headway between the trainsets will therefore be longer.

It can therefore be concluded that the utilisation of both tunnels is low since both tunnels will have unused capacity for more trains. It can also be concluded that the number of 42 S-trains in each direction in two tunnels in total is low since 30 S-trains in each direction per hour run through the Boulevard Tunnel today and it is proposed that this number could be reached to at least 33 or 36.

However, as illustrated in Figure 49 the bottlenecks in the network are not located in the central parts of Copenhagen but on the radial lines due to the skip-stop-service and the single-track line between Fiskebæk and Farum.

Furthermore, it is also noticeable that the S-train network has other tracks where more S-trains can reverse. This is especially the case for Østerport with the platform track 13.
which in S20 is applied to reverse line H every 20 minutes. In Scenario 1 and Scenario 2 track 13 is not used anymore which means that a potential track for reversing S-trains is now unused. The stations Vanløse, Herlev, Glostrup and especially Lyngby have also a track to reverse S-trains according to the schematic track layout plans\(^\text{17}\) in Appendix 1. In the meantime, these tracks are useful if interruptions occur on the radial lines in the network since it will not be necessary to cancel a train to e.g. Vanløse or Herlev if an incident occurs in, for instance, Skovlunde. Furthermore, another reason for not including these tracks is that it will be difficult to find a path for the additional S-trains from the station with a depot track to another station without affecting the other trains in the network. It means that even though the capacity is increased in the central part of the network, new bottlenecks will occur on the existing infrastructure since these lines will be used by trains in the Boulevard Tunnel and in the Express Tunnel at the same time.

Finally, it is also observed from Figure 48 that Hellerup Station is a complex station with many conflicting train routes. Even though that more trains on the radial lines from Klampenborg or Holte and Hillerød would be an option, it will be even more difficult to secure the train movements through Hellerup Station. Therefore, Hellerup Station will remain a bottleneck for more trains from the Hillerød- and the Klampenborg-branch if the station still has many intersecting and diverging conflicts. It might be relevant to investigate a reconstruction of Hellerup Station for avoiding these conflicts. This has not been an approach in this project since an investigation of this problem would be complex and outside the scope of this project.

8.2 Passenger flows and travel time savings
As observed and commented in chapter 6.5, the passenger flows in the public transport network will change after the implementation of the Express Tunnel. It is expected that the implementation of the new tunnel causes a decrease in the number of passengers for the S-train line through the Boulevard Tunnel and line F as well since the Express Tunnel is a faster alternative from north to south. The main differences in the passenger flows in Scenario 1 are illustrated in Figure 67. This map is also included in Appendix 6.

\(^{17}\) These tracks are denoted as 21, 0, 34 and 2 for Vanløse, Herlev, Glostrup and Lyngby respectively.
Figure 67: Differential maps in train passenger flow (absolute differences) in Scenario 1. Red links are increased passenger flows and blue links are decreased passenger flows.

The main differences in Scenario 1 are approximately the same in Scenario 2 and, therefore, the same differences are commented. It is noticeable that other lines outside the S-train network have a passenger decrease. This is especially the case for the line Copenhagen Central Station-Copenhagen Airport and it is assumed that this line is highly affected by the changed S-train network. In the current network interchange to the regional train towards CPH Airport – and Sweden – is possible at the stations on Østerport, Nørreport and Copenhagen Central Station. But since the S-train service for these stations is significantly reduced the passengers cannot change from the removed S-train lines to this regional train. However, the S-train lines E, H and K stop at Forum Station where interchange to the metro line M2 towards the airport is possible. This is also illustrated in Figure 67 – a passenger increase is expected at the metro line from Forum to the airport. It can then be concluded that an increase in the passengers in the metro and a decrease in the regional train to and from the airport is likely since the interchange opportunities to the metro are improved and reduced to the regional train. The passenger decrease for the branch to Hillerød is assumed to be caused by longer travel time to and from the stations Østerport, Nørreport and Copenhagen Central Station in the city. Furthermore, it is also observed that a decrease for the local trains in Northern Zealand including Nærumbanen is expected even though that no adjustments of this
network is carried out. It is assumed that the main reason for this decrease is the changed timetable of line E from Hillerød and line B from Jægersborg. The timetables for the local trains are not adapted to the new S-train timetables and, consequently, the changing time to the S-trains might be increased and the generalised costs for selecting the local trains in the trip is increased.

It is also noticeable in Table 13 that the intercity trains as well as the regional trains operated by Arriva have a decrease in the number of passengers even though that these transport modes are not directly affected by the Express Tunnel. It is assumed that it is a domino effect from the changed S-train network since fewer S-trains stop at Copenhagen Central Station where it is possible to change to the long-distance trains, IC-lyn, which does not stop at other intercity stations such as Høje Taastrup, Valby, Ny Ellebjerg or Køge Nord with interchange opportunities to S-train. Fewer passengers in these trains to, for example, Aarhus might result in fewer changes to regional trains by Arriva. However, as commented earlier, the decrease is very small and not significant in the overall passenger flow.

It can also be discussed if the new network of S-train lines is the optimal network in the light of the socio-economic analysis. The free travel time, the vehicle time, is improved significantly in the network after the implementation of the Express Tunnel and it is therefore a main benefit for the society. This is also the case for the waiting time since this also is listed as a benefit – the passengers will experience less time for waiting at the public transport mode.

However, the hidden waiting time has only a minor positive value which means that this is whether improved nor reduced. The number of trains on the majority of the radial branch lines is increased which means that the headway between the trains is reduced. In the meantime, the number of trains is reduced significantly in the Boulevard Tunnel which increases the hidden waiting time for many passengers at these few stations. It is also noticeable that the improved vehicle time in the network is to the detriment of more changes since the changing time is a cost as well as the penalty value for the changes. It is assumed that this is a primary impact for operating the lines E, H and K via the Express Tunnel which means that these lines are not connecting other cities such as Hillerød, Frederikssund and Køge with direct S-trains to Copenhagen Central Station or other stations in the inner parts of Copenhagen. These passengers will have to change to another train for arriving to or departing from these stations.

It is therefore assumed that a better performance for the Express Tunnel would be expected if the other adjacent networks to the S-train network, e.g. the local train lines, are adapted to the new timetables for the S-trains. This is, however, not conducted in this project since the main focus is the Express Tunnel only and its benefits to the public
transport network. Furthermore, a more detailed investigation of changing passengers is also a recommendation.

8.3 LTM vs OTM

It can also be discussed if the National Transport Model is the best model for investigating a new tunnel for S-trains or new extensions of the public network in Copenhagen in general. Since Denmark in LTM is divided into 907 zones and is applicable for new national projects, such as new intercity train services, the level of detail for the Greater Copenhagen Area might be too low and will not take other internal trips within one specific zone in Copenhagen into account. However, another model, the Oresund Transport Model (OTM), covers the Greater Copenhagen Area in approx. 840 zones which means that the level of detail is highly increased for this area (Rasmussen, 2017). It is therefore recommended to test the performance of the Express Tunnel in OTM as well in order to detect more detailed results.

One of the short-comings of LTM is especially when two stations are located very close to each other. In some cases they are located in the same zone and it means that the distribution of passengers between these stations would be too inaccurate. One example on this problem is the terminus Orientkaj for Nordhavnsmetroen. This is located in the same zone as the following station Nordhavn and both stations are connected to the same centroid. But the centroid is located closer to Nordhavn than to Orientkaj with a lower connector travel time which means that no passengers use the station Orientkaj. It will always be faster for the passengers to use Nordhavn. However, Orientkaj would in a real situation be used by passengers that live in the future urban area located at this station. Another shortcoming of LTM is uncertainty with calculation of trips in new urban areas such as Nordhavn in Copenhagen or Vinge at Frederikssund. For such cases, the knowledge about trips or transport demand is limited since the areas need to attract residents before the knowledge can be determined.

On the other hand, LTM has a benefit for this project since it has been possible to identify passenger changes in the long-distance trains as well as identifying the changes within the Greater Copenhagen Area. In this case, a decrease in passenger km has been observed for intercity trains even though these are not directly affected. However, the decrease is very low and it is assumed that it is insignificant. Furthermore, this model is also based on available and well-known software from the beginning.

8.4 Operation issues

Regarding the operations of the S-trains it can be stated that there is one major disadvantage with the suggested alignment for the S-trains or with other alternative timetable suggestions. Today, all S-train lines except line F run through Copenhagen Central Station which has four platform tracks and many depot tracks. In this case, it is possible to reverse trains from south and from north at Copenhagen Central Station and to
take them out of operation which is relevant in order to raise and to lower a headway at a specific line.

However, with the new Express Tunnel this is not an opportunity for trains running through the new tunnel since the depot tracks are missing – only at the terminus stations in the S-train network is an option for this process. It means that no trains on lines through the Express Tunnel can reverse on the central part but only at terminus stations on the radial lines. Furthermore, the headway cannot be increased in the morning or lowered in the evening which means that the same train units have to continue to a terminus station. With the existing tunnel today, a train from e.g. Hillerød in the evening hours can be taken out of service at Copenhagen Central Station if the number of passengers on the branch to Køge is lower in these hours, which means that it is not necessary to keep the same headway in these hours. This opportunity does not exist for the Express Tunnel and, consequently, the trains have to continue to a terminus or at least a station with a depot track, and this raises the operational costs.

Another main disadvantage with the proposal for operation and alignment is Hellerup Station. The Express Tunnel including more lines and higher headways leads to a higher utilisation of the platform tracks at this station. It also leads to not isolating line F from the remaining S-train lines since the new lines will occupy the platform tracks at Hellerup, tracks 5 and 7, which only are used by line F today in normal operation. It means that an occupied tracks could cause a delay for line F.

It is out of the project’s scope to demonstrate a reconstruction of Hellerup Station and a digitalisation of it in RailSys, since the scope is based on the Express Tunnel only. However, it is considered that a reconstruction is able to solve the challenges and conflicts and isolate line F.

### 8.5 Strategic effects

A strategic effect from the Express Tunnel is primarily that new areas in Copenhagen, which are not served by S-trains today, will be connected to the S-train network and direct connections from the suburbs on the radial lines to other areas of Copenhagen are established. Furthermore, Scenario 2 also illustrates that an urban area of Copenhagen and an area with a high number of jobs and university students now is served by high-classed public transport. It is worth mentioning that the existing metro station at Trianglen is close to Rigshospitalet and passengers could easily reach the hospital by changing to buses, but as the results from LTM illustrated, there is clearly a demand for establishing a new station at this location.

Finally, the project behind the Express Tunnel has some other effects on which it is difficult to assign a monetary value for the cost-benefit-analysis. A major benefit is the tunnel itself as an alternative for the Boulevard Tunnel in case of interruption in the Boulevard Tunnel which affects all S-train lines except line F. An incident like a personal collision has enormous impacts on the operation for a long time period, and since an
incident in the Boulevard Tunnel causes interruption and delays for many passengers the monetary value of lateness will lead to a high socio-economic loss. In such cases, the S-train lines could use the alternative tunnel and the passengers would probably be willing to take the S-train to e.g. Forum station and change to the metro, if their destination is Nørreport or Copenhagen Central Station by changing to Cityringen. In this case, a new tunnel maintain the robustness not only in the S-train network, but in the public transport network in general.

This major benefit of a new alternative tunnel for the S-trains illustrates one of the shortcomings in a cost-benefit-analysis. The CBA only includes benefits and costs on which it is possible to assign a monetary value and is only depending on findings on travel time savings from an assignment model from where it is not possible to get any results about an increased robustness level or at least if the level of lateness is likely to decrease. It then means that a CBA only tells a part of the whole truth and it is therefore recommended to present further results from other analyses like a simulation of the operation.

8.6 Alternatives to the investigated alignment

This report suggested and studied two different alternatives for an alternative to the existing tunnel via Nørreport Station. Therefore, the study for an alternative is not complete and this chapter will introduce and discuss some alternatives.

The alignments for Scenario 1 and Scenario 2 are, as illustrated throughout the report, almost identical, whereas the only difference is the additional station at Rigshospitalet in Scenario 2. One advantage with rescheduling the lines in the new network as well as its alignment is the opportunity for obtaining short travel times from the northern radial branch lines from Farum, Hillerød and Klampenborg to the stations Vibenshus Runddel and Forum, at which it is possible to change to the metro lines M3 as well as M1 and M2 respectively. Today, the travel time Hellerup to Østerport, at which a change to M3 is possible, is 8 minutes, but with the Express Tunnel and the station at Vibenshus Runddel, the travel time to the first station, at which the same change can be obtained, is reduced by 4 minutes. Furthermore, the shortest travel time from the Farum-branch to and from M3 is 10 minutes via Østerport in S20, and the travel time with the Express Tunnel from Emdrup Station to Vibenshus Runddel is 4 minutes. Hence, a significant travel time reduction from the northern branch lines towards the metro lines are obtained with the Express Tunnel.

However, the connections and travel time from the southern branch lines from Køge, Høje Taastrup and Frederikssund are only improved to line M1 and M2 at Forum Station. The travel time from Sjælland Station to Forum is 5 minutes whereas it will be 4 minutes from Valby. But 3 minutes of travel time has to be added if the passengers would travel further to Vibenshus Runddel which will result in a travel time by 7-8 minutes from Valby and Sjælland respectively. Today, the travel time by S-train from Valby as well as Sjælland to
Copenhagen Central Station is 7 minutes which means that the lines via the Express Tunnel do not provide shorter travel times from the southern branches and stations to Cityringen but only to M1 and M2.

For dealing with this issue, a new scenario, Scenario 3, is considered. In this case, a new station on the Express Tunnel is located at the existing Frederiksberg Station as a replacement for Forum Station. At Frederiksberg, interchange opportunities are possible to both M1 and M2 as well as M3, since both metro systems have a station here. It is assumed that the length of the branch from Valby/Sjælør is approximately the same as for the branch to Forum, which means that shorter travel times to Cityringen would be obtained with this solution. If Scenario 2 with Rigshospitalet is combined with Scenario 3, a new Scenario 4 could also be investigated. These alignments are illustrated in Figure 68 below.

Figure 68: Alternatives for Scenario 3 and Scenario 4. The new alternatives include a station at Frederiksberg as a replacement for Forum.
With the alternatives 3 and 4, it will be possible for the northern branch lines as well as the southern branch lines to get access to M3 with travel time reductions compared with the network today and Scenario 1 and Scenario 2. Since this project’s scenarios and S-train operation indicated a huge number of passengers at Rigshospitalet, it is suggested that Scenario 4 should be implemented. However, a new S-train station at Frederiksberg will be complex to construct since two metro tunnels already exist at this location. It means that the new S-train tunnel would be constructed below the existing two metro stations.

If it is decided to keep either Scenario 1 or Scenario 2, an option for avoiding the longer travel time from the radial lines to Cityringen (M3) is to establish a third interchange station at the existing metro station Frederiksberg Allé. In this case, it will be possible to reduce the travel time significantly to and from Cityringen by comparison with the travel time to and from Copenhagen Central Station. However, the travel time to the other stations in the Express Tunnel will increase. It is therefore recommended to analyse if this investment has higher benefits than the disadvantages with a longer travel time for other passengers.

Another option for an alternative line to the existing tunnel via Nørrebro is to use Ringbanen via Nørrebro. Today, this line is only connected to the S-train network in Hellerup at the remaining interchange stations at Ryparken, Flintholm, Danshøj and Ny Ellebjerg, but no connections to the intersecting S-train lines are established. If a shunt from the other lines to Ringbanen were constructed, it would be possible to run trains from e.g. Høje Taastrup to Farum or Hillerød along Ringbanen. Ringbanen is today only served by line F every 5 minutes which means that 12 trains in each direction per hour in daytime hours utilise the line. As illustrated in Table 3, a capacity consumption when CBTC is rolled out by 27.0% and 30.0% depending on the direction is reached. It means that the line is still able to carry a higher number of trains than today. However, the same stopping pattern should be kept for all trains on the line for avoiding a higher capacity consumption and a more unstable operation according to Figure 24.

By investigating this idea shortly, the following advantages and disadvantages are identified:

**Advantages:**
- **Shorter travel times between the radial lines**

Today, the travel time between e.g. Hellerup and Ny Ellebjerg with line A and E in S20 is 23 min via Nørrebro. The travel time with line F is, however, 18 min, but the reduction in travel time from the Hillerød-branch to Køgebugtbanen cannot be reached since the
passengers have to change twice for obtaining the reduction. If the lines could continue along Ringbanen, the reduction would probably be 5 min.

- **Alternative line as a supplement to the Boulevard Tunnel**
  The same benefit from the Express Tunnel applies to Ringbanen, if Ringbanen is connected to the other lines in the network: It would be possible to operate trains along Ringbanen if the Boulevard Tunnel is interrupted.

- **More direct connections to and from other stations in the network**
  With new lines along Ringbanen and connections to other radial lines, direct connections from densely populated urban areas in Copenhagen like Nørrebro could be established to suburbs with job opportunities and universities like DTU in Lyngby. In this case, changes between S-trains would be reduced and the total travel time would also be reduced.

**Disadvantages:**

- **Construction of new infrastructure**
  New structures like bridges and tunnels should be constructed around the interchange stations in order to connect Ringbanen to the radial lines. This part is assumed to be highly critical at especially Flintholm Station at which it will be necessary to demolish and rebuild the station as well as the metro line crossing Ringbanen. Furthermore, it will also - like for the Express Tunnel - be necessary to interrupt the S-train lines at the locations where the new infrastructure should be connected to.

- **Ringbanen is not isolated**
  Today, line F is characterised as an isolated line from the other lines in the S-train network. It means that it will not be affected by incidents happening at other locations and stations in the remaining network. Consequently, Ringbanen had a high customer punctuality by 96.0% in 2016 and 96.8% in 2017 (Passagerpulsen, 2017). But if other delayed trains from the radial lines should continue along Ringbanen, the delays will also affect the punctuality on Ringbanen.

- **Changed headway**
  Line F has today a 5 min headway on Ringbanen in daytime, which means that the hidden waiting time is steady throughout the day. However, if different lines independently from each other should run on the line, the headway would probably change from e.g. 5 min to 3-7 min between the trains.

- **The line does not serve new areas**
  Finally, no other stations or new areas will be covered by S-trains or metro. It means that other lines should be constructed to service new areas such as Rigshospitalet.
This report has not investigated this idea in detail, but it is highly recommended that it should be analysed. Moreover, it should also be evaluated if all possible shunts from all radial lines should be constructed or if some of them could be omitted.

### 8.7 Cost estimation and reserve

Another critical parameter for deciding and adopting the construction of the Express Tunnel is the construction budget. In this project, the construction budget is based on different references for other railway projects, but this method has many shortcomings since many uncertain factors are not taken into consideration. For instance, this project, and especially the cost estimation, does not concern several obstacles for the tunnel such as cables and pipelines in the ground. It is assumed to be very likely that some cables and pipelines might be an obstacle for the Express Tunnel and reconstructions of cables and pipelines are an expensive post for a construction project. One example is the construction of the new light rail line on Ring 3 in which the cost for reconstruction of cables was estimated to 51 M DKK\(^\text{18}\) per km of light rail line (Ring 3 Letbane I/S, 2016). Furthermore, it is also expected that the construction of the tunnel will lead to massive nuisances for the existing passengers since the existing S-train lines and also regional lines have to be interrupted for a long time interval when the junctions to and from the new tunnel have to be built. Consequently, this will lead to an additional socio-economic cost since the travel time in such periods will increase significantly and passengers might change to other transport modes such as other lines or replacement buses.

This uncertainty is, however, a usual problem with estimating a construction budget in an early stage. Therefore, Bent Flyvbjerg and COWI published in 2004 a report about estimating construction costs with different cost uplifts compared to the certainty. The uplifts and acceptable optimism bias depend on the project since it is considered to be different from a road project to a railway project and a project about a fixed link. A railway project includes in this case metro projects, high speed rail project and fixed link projects with bridges and tunnels such as the Øresund Fixed Link (Leleur, Salling, Pilkauskiene, & Nicolaisen, 2015). These values are listed in Table 23 below.

<table>
<thead>
<tr>
<th>Level of acceptable optimism bias</th>
<th>50%</th>
<th>60%</th>
<th>70%</th>
<th>80%</th>
<th>90%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Road</td>
<td>15%</td>
<td>24%</td>
<td>27%</td>
<td>32%</td>
<td>45%</td>
</tr>
<tr>
<td>Rail (and air)</td>
<td>40%</td>
<td>45%</td>
<td>51%</td>
<td>57%</td>
<td>68%</td>
</tr>
<tr>
<td>Fixed Link</td>
<td>23%</td>
<td>26%</td>
<td>34%</td>
<td>55%</td>
<td>83%</td>
</tr>
</tbody>
</table>

Table 23: Overview of different construction costs reserves depending the level of optimism bias (Leleur, Salling, Pilkauskiene, & Nicolaisen, 2015).

\(^{18}\) In price level 2013.
Table 23 illustrates, for instance, that a railway project should be corrected with a 57%-reserve if the level of acceptable optimism bias should be 80%. More specifically, in case of a cost overrun must be less than 20% for a railway project, a construction cost estimate by 100 million DKK must be raised to 157 million DKK. In this case, it is ensured with 80% probability that the final investment cost will not surpass 157 million DKK.

If the cost estimate for the Express Tunnel is applied to this investigation, the correctional reserve 40% should be added if the level of optimism bias is 40% or with 57% if the level should be 80% instead. Consequently, the reserve by 40% results in an IRR by 1.0 for Scenario 1 and by 1.5% for Scenario 2. With the high reserve, the IRR is 0.8% for Scenario 1 and 1.3% for Scenario 2.

Finally, when the project is investigated in more details with a higher level of certainty in connection to the construction costs, the level of a correctional reserve might be lower than 50% according to NBP phase 1. This is also the case today when the second phase, the program-phase, where the correctional reserve is reduced to 30%. After this phase, more uncertainties in the project should be clarified which leads to the reduction.

8.8 S-train profile
Another investigation, which is outside this project’s scope, is to consider the new class of rolling stock for the S-train network in the future. Since the current fleet of SA/SE trainsets are from 1997 to 2005, the trainsets might be replaced by newer trainsets from 2030 - or when a new S-train tunnel could be finished. In this case, it would be interesting to consider the design of the future S-train fleet since the design of the train and the clearance profile have an influence on the cross section profile of a tunnel. If the new S-trains have a smaller profile than the existing fleet, it might be possible to reduce the diameter in the cross section which minimises the cost for the tunnel.

Figure 69 to the right illustrates the different clearance profiles for an S-train on specific S-train lines with a speed limit up to 120 km/h. The profile SA is a general profile that always must be respected whereas SB refers to profiles at bridges and other constructions and SD to the least acceptable profile for infrastructure in operation. The profile A is an additional profile if an S-train line also should be used by freight trains.
As illustrated, the profile SA is much higher than the profiles SB and SD which means that the pantograph on the S-trains require a higher profile in tunnels. In the meantime, the metro trainsets in Copenhagen operate in bored tunnels as well as specified for the Express Tunnel, but since the metro trains have another profile and use a third conductor rail along the track instead as an ordinary overhead catenary wire or an overhead conductor rail, the cross section can be smaller. More specifically, the metro trainsets are not equipped with a pantograph on the roof on the trains by comparison to the S-trains. It means that the cross section profile in the metro system can be smaller and one requirement for the upcoming S-train fleet could be that the rolling stock should be able to run on both an overhead catenary system and a third rail. This will, however, affects the cost of the rolling stock whereas the cost of the construction could be reduced significantly.

8.9 Proposal for further analyses
Currently, other analyses for proposals of S-train extensions are undergoing in the upcoming years. It means that these proposals could be discussed in connection to the Express Tunnel for new investigations. The mentioned projects are only proposals based on current undergoing projects and should therefore be thought of ideas for further analyses of scenarios with the Express Tunnel.

8.9.1 S-train to Roskilde and Helsingør
At December 12th, 2019, the Danish Transport, Construction and Housing Agency published a report about implementation of automatic/driverless S-trains to Roskilde. This operation should be an extension of the existing S-train line to Høje Taastrup, from where the S-trains to Roskilde can continue towards Roskilde with stopping at the stations Hedehusene and Trekroner. These stations are served by regional trains today, and the report states that an S-train service will increase the number of stopping trains at these stations (The Danish Transport, Construction and Housing Agency, 2019).

Today, the line for long-distance trains between Høje Taastrup and Roskilde has four tracks and electrified with 25 kV 50 Hz AC for these trains. In the meantime, the report suggests that two tracks should be used by S-trains and the overhead catenary system for these tracks should be reconstructed to 1,650 V DC for the S-trains. The report also suggests that the existing lines on the Høje Taastrup-branch, B and Bx, are changed and both lines then have a 10 minutes headway, but line B skips the stations Brøndbyøster, Rodovre and Hvidovre and continues to Roskilde and line Bx is a stopping train with Høje Taastrup as terminus. If this idea should be investigated with the Express Tunnel, a proposal could be to continue line K towards Roskilde and keeping the same stopping pattern as in the original proposal. However, a new analysis should be carried out since line K does not run towards Copenhagen Central Station as in the report, but towards the Express Tunnel. It means that it should be analysed if the passengers rather would prefer
direct S-trains towards Copenhagen Central Station and Nørreport or as faster transport mode to other radial lines in the network.

Back in 2011, another screening about S-trains to Roskilde, but also to Helsingør, was published by the Danish Transport, Construction and Housing Agency. With S-trains to Helsingør, the report suggested S-trains on the line to Helsingør, Kystbanen, with a stopping train to Nivå and a skip-stop-service to Helsingør as today. Both lines should run with a 10 minutes headway in daytime hours. With this scenario in connection to the Express Tunnel, it could be possible to run line K towards Helsingør in the skip-stop-service and line C to Nivå. Both lines should, however, use the existing tracks for the regional trains to Nivå and Helsingør, and the regional trains could in this scenario have Hellerup Station as terminus. An implementation of S-trains on Kystbanen would in this case require a reconstruction of the platforms to S-trains as well as a new overhead catenary system. However, due to the low number of passengers on the stations Charlottenlund, Ordrup and Klampenborg in Scenario 1 and Scenario 2, it is assumed to be a relevant solution to attract more passengers on line C and line K.

Figure 70: Example on an extension of line K to Roskilde and Helsingør as well as line C to Nivå.
Since the projects about the S-trains to Roskilde and Helsingør are not decided at the present moment, it is recommended that an analysis of these projects connected to the Express Tunnel will await a potential decision.

8.9.2 Extension of the Farum-branch
Another bottleneck in the S-train network is the short single-track line from Fiskebæk to Farum. As identified in this report, it is not possible to operate more S-trains to Farum Station since these trains will conflict on the single-track.
A double-track across Mølleåen with a new bridge and a new track to Farum Station will eliminate this bottleneck since a train at Farum Station can depart from the station without waiting for the oncoming train. This is, however, not a new proposal for an extension of the S-train network since an extension of the Farum line already has been proposed some years ago. At this time, it was proposed by the municipality of Furesø, which covers Værløse and Farum, that the Farum-branch could be extended from Farum towards Allerød and Hillerød and be connected to Nordbanen (Atkins, 2012). The new alignment should be extended towards Allerød Station and in this way create new direct connections from Værløse and Farum to Allerød and Hillerød including the new hospital at Favrhholm Station. Figure 71 to the right illustrates, how an extension could look like according to the report “Forlængelse af Farumbanen til Nordbanen” by Atkins from 2012. With this proposal, line H can be extended to Hillerød and line A can reverse in Farum. Since a double-track from Fiskebæk to Farum as well as a relocation of Farum Station is included in this analysis, both line A and line H can have a 10 minutes headway. Since the capacity consumption between Holte and Hillerød according to Table 3 is low, it is assumed to be possible to operate two lines every 10 minutes on this line. Another strategical benefit from this extension combined with the Express Tunnel’s Scenario 2 is that Rigshospitalet and the new hospital at Favrhholm will be connected directly with two S-train lines.

8.9.3 Utilisation of remaining capacity in the network
One of the main points in Scenario 1 and Scenario 2 is that the S-train network still have bottlenecks that limit the total number of trains in the network. Even though that the capacity consumption is significantly reduced between Dybbølsbro and Svanemøllen, the bottlenecks on especially Hellerup-Holte and Dybbølsbro-Hundige will still remain since the skip-stop-service is a limitation on the number of trains on these lines.
From the assignment model, it could be concluded that a huge number of passengers will still have Nørreport Station as destination which means that a high number of trains per hour is needed. In the meantime, the operation in the tunnel via Nørreport is reduced by 6 trains during peak hours whereas only 18 trains per hour will use the Express Tunnel,
even though that the capacity consumption is low. Consequently, it will be possible to
operate more S-trains in the existing Boulevard Tunnel via Nørreport and in the Express
Tunnel, but the northern radial lines except Hellerup-Klampenborg as well as Valby-
Frederikssund and Dybbølsbro-Hundige remain a bottleneck for more trains. Hellerup-
Klampenborg will still have unused capacity after the introduction of line K, but since the
number of passengers on this line is much lower than for the remaining radial lines, it is
considered that the demand on this line is satisfied.
As described in chapter 3, the new signalling system CBTC does not increase the capacity
significantly on lines with skip-stop-service since the combination of stopping trains and
fast trains utilises the capacity up to UIC max. The disadvantage with this service was
already described by Alex Landex and Niels Wellendorf in 2008, when the original idea
behind a new S-train tunnel in Copenhagen was proposed. It was pointed out in their
report that overtaking loops on the lines with a high capacity consumption as a
consequence from skip-stop-service would enable more – and especially faster – S-trains
on the radial lines. One example was from Holte-Hellerup, on which an overtaking loop
enabled a new line from Hillerød every 10 minutes in combination with line B and E.
Another option to utilise the lines with more S-trains is to abolish the principle about skip-
stop-service on the radial lines and instead introduce a more homogenous metro-style
concept as illustrated in Figure 24. The figure illustrates that a metro-style concept results
in more trains, a more stable system but a lower average speed. This will also be the
consequence for e.g. Hellerup-Holte at which all trains will stop at the same stations. The
benefit from this system is a shorter headway time on some stations and a shorter hidden
waiting time. The main disadvantage is, however, that passengers on stations, which the
fast trains stop at, will experience an extended travel time since the fast trains have to stop
at more stations.

A metro-style timetable on the line Hellerup-Holte-Hillerød has been investigated since
this is one of the lines with the highest capacity consumption. In this timetable it is
assumed that two lines are in operation: One line Hellerup-Hillerød and one line
Hellerup-Holte. Both lines have a headway by 5 minutes and stop at all stations. The two
different timetables from RailSys are illustrated in Figure 72 below.

![Figure 72: Metro-style timetable vs. skip-stop-service in Scenario 1 and Scenario 2 between Hellerup and Holte.](image)
As observed in Figure 72, it is possible to operate more trains with the metro-style timetable since the line can be served with 24 trains per hour contrary to 12 trains per hour with the skip-stop-service. Furthermore, the capacity consumption is also reduced. With the skip-stop-service, the capacity consumption between Hellerup and Holte is only 54.7% compared to 75.2% with the skip-stop-service. Hence, it is possible to increase the number of trains on the line and reduce the capacity consumption at the same time with a metro-style timetable. It is with this timetable possible to operate the lines from Holte and Hillerød towards both tunnels every 10 minutes. The main disadvantage is, however, that the travel time between Hellerup and Holte is increased with 6 minutes.

Since an analysis of a new metro-style concept or a construction of overtaking loops on the radial lines easily would be another project in addition to the analysis of the Express Tunnel, the consequences behind these proposals have not been investigated in detail. However, it is highly recommended that this investigation should be carried out before the decision of an extension of the network in the central parts of Copenhagen.

8.10 Final recommendation

Finally, it is highly recommended that the Express Tunnel should be investigated in further analyses since several factors regarding the construction costs are too uncertain on the current stage. It is also recommended that a similar analysis like the analysis in this report should be conducted in OTM in order to analyse the benefits of the Express Tunnel in a model with a more detailed level of zones in the Greater Copenhagen Area. For this analysis, it should also be investigated if the tunnel can replace bus lines and if an adaption of the bus network can be done in order to save operational costs for the buses. Another recommendation is that the timetable for other public transport modes in the network should be adapted to the new timetable for the S-trains. In this project, only the timetable for the S-trains is adjusted with the new infrastructure, but other transport modes with interchange to the S-trains at the termini should also be changed. This is, for instance, the case for the local train service from Hillerød and Køge from where this transport mode has an interchange opportunity to the S-trains, and since the S-train timetable is changed some passengers might get longer changing time to and from the S-trains. This is, however, not the primary focus in this report, but it is considered that the new network will get a higher benefit from these adjustments.

Furthermore, Trængselskommissionen suggests in the report from 2013 that a socio-economic analysis of the development of the S-train network should be done in order to select specific locations on the network for upgrade and extension. The primary purpose with this analysis is to evaluate on the demand and the opportunities for an improved network if more passengers should use the public transport and more passengers have access to direct connections to and from the central parts of Copenhagen and the suburbs.
The consequences of a metro-style timetable versus the current operation with skip-stop-service should also be evaluated in combination with driverless operation (Trængselskommissionen, 2013). Therefore, this report recommends that a future analysis of the Express Tunnel should take a metro-style timetable into consideration as an alternative to the current skip-stop-service since this project illustrated that a skip-stop-service on the radial lines – without upgrades or extensions – is a problem for operating many trains in the new Express Tunnel and in the existing Boulevard Tunnel. The primary focus in this analysis should be to evaluate on the travel time savings, and it should therefore be analysed if it is better to reduce the travel time with few fast trains or to reduce the waiting time, the hidden waiting time and changing time with many, but slower direct trains between the radial lines and the lines in the city centre. This analysis has not been a part of this project’s scope, but it seems relevant to do it in order to utilise the untapped potential of the Express Tunnel.

9 Conclusion
The public transport network in the Greater Copenhagen Area consists of many different transport modes and each of them has their own primary function. The most intensive train network is represented by the S-trains which connects the inner parts of Copenhagen with the suburbs and other cities around Copenhagen and is designed based on Fingerplanen. The central part of the network – the Boulevard Tunnel – could possibly undergo a change in the upcoming years with a higher capacity for S-trains as a benefit from the new signalling system CBTC.

However, the Boulevard Tunnel, or more specifically the stations Svanemøllen-Dybbølsbro, is still accountable for a huge share of the incidents that cause delays and cancellations in the entire network since all S-train lines except line F run via this bottleneck. Furthermore, the average travel time between the southern parts and the northern parts is not improved even though new lines in the metro network have been built or will be built in the future. An alternative tunnel, the Express Tunnel, might solve these problems, since the S-train lines can then run via two tunnels and the travel time between the radial lines can be improved.

With the implementation of such a new tunnel, it is possible to reduce the travel time by S-train between the radial lines by between 5 and 14 minutes depending on the origin and destination and whether it is necessary to change to another line. The travel time reduction is based on the suggested and investigated service and if the number of trains in the Express Tunnel will be higher, the reduction between other relations might be reduced even further since an interchange between trains can be omitted. Since the existing skip-stop-service on the radial lines is kept and not changed to another operation concept it is not possible to utilise the capacity of both tunnels – the Express
Tunnel and the Boulevard Tunnel – at the same time. The lines Dybbølsbro-Hundige, Hellerup-Holte, Værløse-Farum and Valby-Ballerup as well as the stations Valby and Hellerup will be the new bottlenecks in the network.

The analysis is based on two scenarios, Scenario 1 and Scenario 2. Scenario 1 includes an alignment of the Express Tunnel with only two stations: Forum and Vibenshus Runddel. Scenario 2 includes a slightly changed alignment and an additional station at Rigshospitalet and with the route choice calculations in the National Transport Model it can be concluded that Scenario 2 leads to a higher passenger increase in the Express Tunnel and in the S-train network in general. Especially the additional station at Rigshospitalet has a high passenger load and even though this station extends the travel time in the Express Tunnel compared to Scenario 1 and leads to higher construction costs, Scenario 2 is more socio-economically profitable compared to Scenario 1 since the travel time savings and other benefits are higher in Scenario 2. It can thus be concluded that Scenario 2 is the most preferred scenario. However, none of the scenarios are socio-economically profitable in general since both scenarios have a negative net present value and an internal rate of return below the discount rate. The sensitivity analyses will not make the scenarios socio-economically profitable and it can thus be concluded that higher travel time savings or other impacts should be the basis for deciding whether such a construction should be undertaken. Furthermore, no significant difference in the number of cars on the main roads in the Greater Copenhagen Area is expected and in the same time a decrease in the number of passengers on other lines and for other transport modes in the Greater Copenhagen Area is also a result from the analyses.

This report finally recommends that the Express Tunnel should be further analysed in order to determine other beneficial or detrimental effects. A possible venue for further analysis is a simulation of the suggested S-train operation or other timetable scenarios as well as an evaluation of the consequences of skip-stop-service on the radial lines vs. a metro-style operation. It is, however, assumed that a new scenario with a higher utilisation of both tunnels in the central parts of Copenhagen will be of great significance for an implementation of the project.
10 References

Den Store Danske. (16. June 2017). Københavns Metro. Hentet fra http://denstoredanske.dk/Bil,_b%C3%A5d,_fly_m.m./Jernbane/Lokal_jernbanetransport/K%C3%B8benhavns_Metro


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Appendix 1: Schematic drawing of S-train infrastructure

1. Skelbæk-Høje Taastrup:
   - Towards Frederikssund
   - Valby (Val) km 4.8
   - Carlsberg (Cb) km 2.6
   - Skelbæk (Sib) km 1.3
   - Towards Køge
   - Glostrup (Gl) km 11.2
   - Brøndbyvester (Bøt) km 8.5
   - Rødovre (Rdo) km 7.4
   - Hvidovre (Hvit) km 6.3
   - Danshøj (Dah) km 5.3

2. (Skelbæk)-Køge:
   - Åmorken (Am) km 6.3
   - Ny Ellebjerg (Nel) km 4.4
   - Sjælør (Sja) km 3.8
   - Sydhavn (Syv) km 2.9
   - Bornehøj (Bon) km 2.4
   - Hundige (Und) km 18.7
   - Ishøj (Ih) km 16.4
   - Vallensbæk (Vib) km 14.1
   - Brøndby Strand (Bsa) km 11.9
   - Avedøre (Ave) km 9.6
   - Friheden (Frh) km 7.8
3. (Valby)-Frederikssund:

- Jersie (Js) km 30.8
- Solrød Strand (Sol) km 29.3
- Karlsunde (Klu) km 24.2
- Greve (Gre) km 21.8

- Køge (Kj) km 39.0
- Ølby (Ølb) km 36.3
- Køge Nord (Kjn) km 34.1
- Ølsemagle (Ølm) km 33.0

- Vanløse (Van) km 7.3
- Flintholm (Fl) km 6.8
- Peter Bangs Vej (Pbt) km 5.9
- Langgade (Vat) km 4.8

- Malmparken (Mpt) Km 16.0
- Skovlunde (Sko) Km 15.0
- Herlev (Her) km 12.3
- Husum (Hut) km 10.8
- Islev (Ist) km 9.4
- Jyllingevej (Jyt) km 8.2

- Kildeød (Kid) km 23.1
- Måløv (Mw) km 21.0
- Ballerup (Ba) km 17.9

- Frederikssund (Fs) km 41.8
- Ølstykke (Øl) km 34.1
- Egedal (Egd) km 31.5
- Stenløse (St) km 30.0
- Vekse (Vs) km 26.2
4. (Hellerup)-Klampenborg:

Charlottenlund (Ch) km 10.3
Ordrup (Op) km 11.6
Klampenborg (Kl) km 13.3

5. (Svanemøllen)-Farum:

Ryparken (Ryt) km 7.1
Emdrup (Emt) km 9.2
Dyssegård (Dyt) km 10.6
Vangede (Ang) km 11.5
Kildebakke (Ket) km 12.7

Buddinge (Bud) km 13.8
Stengården (Sgt) km 15.6
Bagsværd (Bav) km 16.8
Skovbyrnet (Skt) km 18.2
Hareskov (Har) km 20.2

Værløse (Vær) km 23.2
Farum (Fm) km 27.3
6. (Hellerup)-Hillerød
Bernstorffsvej (Blt) km 9.2  Gentofte (Gj) km 10.9  Jægersborg (Jæ) km 12.6  Lyngby (Ly) km 13.9

Sorgenfri (Sft) km 15.7  Virum (Vir) km 17.7  Holte (Hot) km 18.9

Birkerød (Bi) km 23.8  Høvelte (Høv) km 26.3  Allersød (Li) km 29.4  Hillerød (Hi) km 36.5

7. (Hellerup)-Ny Ellebjerg:
Grøndal (Ght) Fuglebakken (Fut) Nørrebro (Nø) Bispebjerg (Blt) Km 7.8  Km 8.6  Km 9.7  Km 10.3
Lersøen (Ler) Km 10.6
Ryparken (Ryt) Km 12.0

Ny Ellebjerg (Nel) Vigerslev (Vgj) Vigerslev Allé (Vgt) Danskjæ (Dah) Ålholm (Ålø) KB Hallen (Kbn) Flintholm (Fl) Km 2.3  Km 2.5  Km 3.4  Km 4.1  Km 5.0  Km 5.6  Km 6.6
8. Central part Dybbølsbro-Svanemøllen:

9. Hellerup Station:
## Appendix 2: Timetables for S-trains in Scenario 1

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Note: Platforms A, B, C, D, E, F, H, M1, M2, M3, M4.
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Appendix 4: Public traffic flow in Scenario 1
Appendix 5: Public traffic flow in Scenario 2
Appendix 6: Differential maps for Scenario 1

DTU Transport
Institut for Transport
National Transport Model (LTM)
Changes in no. of passengers in trains
Absolute difference

Frederik Wrona Holgersen

Passengers (AAWT)
Difference

LoadTotal_All_Abs

< -1000
-1000 - -500
-500 - -50
-50 - 50
50 - 500
500 - 1000
> 1000

Main Scenario: 101
Scenario Run: 10003

change ratio in no. passengers (AAWT)
Difference

LoadTotal_All_Rel

< -25%
-25% - -14%
-14% - -5%
-5% - 5%
5% - 15%
15% - 20%
> 25%

Main Scenario: 101
Scenario Run: 10002

OutputRunID: @OutputRun102 (2021-04-16)
Appendix 7: Differential maps for Scenario 2

DTU Transport
Institut for Transport
National Transport Model (LTM)
Changes in no. of passengers in trains
Absolute difference

Frederik Wrona Holgersen

Main Scenario: 102
Scenario Run: 10004

Passengers (AAWT)
Difference
LoadTotal_All_Abs
- < -1000
- -1000 - 500
- 500 - 50
- 50
- 50 - 500
- 500 - 1000
- > 1000

DTU Transport
Institut for Transport
National Transport Model (LTM)
Changes in no. of passengers in trains
Relative difference

Frederik Wrona Holgersen

Main Scenario: 102
Scenario Run: 10004

Change ratio in no. passengers (AAWT)
Difference
LoadTotal_All_Rel
- < -25%
- -25% - -10%
- -10% - -5%
- -5% - 0%
- 0% - 5%
- 5% - 10%
- 10% - 25%
- > 25%

OutputRunID: @OutputRunID (@PrintData)
DTU Transport
Institut for Transport
National Transport Model (LTM)
Changes in no. of passengers in trains
Absolute difference
Frederik Wrona Holgersen

Main Scenario: 102
Scenario Run: 10004

Passengers (AAWT)
Difference > 1:250'000
Load Total_All_Abs
- <1000
- 1000 - 500
- 500 - 100
- > 1000

OutputRunID: @OutputRunID (@PrintData)

DTU Transport
Institut for Transport
National Transport Model (LTM)
Changes in no. of passengers in trains
Relative difference
Frederik Wrona Holgersen

Main Scenario: 102
Scenario Run: 10004

Change ratio in no. passengers (AAWT)
Difference > 1:250'000
Load Total_All_Rel
- < -25%
- -25% - -10%
- -10% - -5%
- -5% - 5%
- 6% - 10%
- 10% - 25%
- > 25%

OutputRunID: @OutputRunID (@PrintData)
DTU Transport
Institut for Transport
National Transport Model (LTM)

Changes in no. of passengers in trains
Absolute difference

Frederik Wrona Holgersen

Main Scenario: 102
Scenario Run: 100004

Passengers (AAWT)
Difference > 1250'000
LoadTotal_All_Abs
- < -1000
- -1000 - -500
- -500 - -50
- -50 - 50
- 50 - 500
- 500 - 1000
- > 1000

OutputRunID: @OutputRunID (@PrintData)

Change ratio in no. passengers (AAWT)
Difference > 1250'000
LoadTotal_All_Rel
- < -25%
- -25% - -10%
- -10% - -5%
- -5% - 5%
- 5% - 10%
- 10% - 25%
- > 25%

OutputRunID: @OutputRunID (@PrintData)
Appendix 8: Daily passenger loads on stations

![Diagram showing daily passenger loads on stations in Høje Taastrup-Copenhagen Central Station and Hillerød-Bernstorffsvej.](image)

- **Høje Taastrup-Copenhagen Central Station**
- **Hillerød-Bernstorffsvej**

Key:
- Basis (TP 2032)
- Scenario 1
- Scenario 2